CIRCUIT BREAKER MONITORING APPLICATION USING WIRELESS COMMUNICATION

A Thesis

by

NITIN VED

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2005

Major Subject: Electrical Engineering

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ABSTRACT

Circuit Breaker Monitoring Application
Using Wireless Communication. (December 2005)

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Circuit breakers are used in the power system to break or make current flow through power apparatus. Reliable operation of circuit breakers is critical to the well-being of the power system and can be achieved by regular inspection and maintenance. A low-cost automated circuit breaker monitoring system is developed to monitor circuit breaker control signals. An interface is designed on top of which different local and system-wide applications can be developed which utilize the data recorded by the system. Some of the possible applications are proposed. Lab and field evaluation of the designed system is performed and results are presented.

To My Parents and Asawari

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CHAPTER I

INTRODUCTION

A. Background

A power system performs the function of generating electric power and making it available at the location where it is required. It is made up of three parts - generation, transmission and distribution scattered over a large geographical region. The power system consists of different electrical and electromechanical apparatus which work together to maintain a continuous supply of power to the consumer. The circuit breaker is one such apparatus whose functioning is critical to the maintenance of constant supply of power. As its name suggests, it is used to make or break the flow of power. It is used to configure the system so as to control the load flow and disconnect the power system from any faulted parts.

Once installed the breaker has a life-time of 20-40 years during which its state changes very infrequently. A breaker has no intelligence of its own. It is operated by power system protection relays which detect faults on the system and identify the appropriate breakers to be opened in order to isolate the faults and allow the system to function. Also, a breaker may be operated through a manual command from power system operators. Sometimes the breaker may not open or close on command, allowing the fault to exist for a longer duration than the system can sustain while functioning normally. Misoperation of breakers can lead to undesired changes in system functioning that result into the system going in an abnormal state. In abnormal state the power apparatus may have to function beyond its ratings and is likely to get damaged. The consequences of abnormal functioning range from

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The journal model is *IEEE Transactions on Power Systems.*

temporary interruption of service in local areas to complete system breakdown. This may cost anywhere from mild inconvenience to loss of millions of dollars. Blackout events in the recent years have demonstrated well the need of having a reliable power system [1]. The circuit breaker forms a critical part of the protection system as well as the Supervisory Control and Data Acquisition system (SCADA) Its operation must be reliable, secure and fast. In order to ensure these features frequent inspection and maintenance must be performed on breakers to detect and repair or replace deteriorating breakers.

Maintenance methods

Power companies employ different maintenance strategies to ensure reliability of equipment operation [2]. Maintenance methods for High-Voltage Circuit Breakers can be broadly classified into 3 groups - Time Based Maintenance (TBM), Condition Based Maintenance (CBM) and Reliability Centered Maintenance (RCM) [3].

Time based maintenance

This is one of the most frequently used maintenance strategies by the power industry. The maintenance intervals are selected on the basis of long-time experience. Table I shows the most frequent maintenance intervals for breakers as reported by the IEEE/PES task force of the reliability, risk and probability applications subcommittee[2]. It is observed that a maintenance cycle may extend to periods as long as over a year and an unnoticed error will leave the system vulnerable to failure. Also, in this strategy, the breaker is replaced at a fixed interval known as breaker lifetime or at failure, whichever occurs first. This maintenance strategy is risky as it can lead to damage of other equipment and loss of power supply.

Table I. Circuit breaker maintenance intervals

Maintenance type	Interval	Duration
Minor maintenance	1 yr	1 day
Minor overhaul	5 yr	3 days
Major overhaul	8-10 yr	2 weeks

Condition based maintenance

In this strategy the condition of the circuit breaker is assessed to determine the time of maintenance. The status of the breaker is usually determined by manual inspection using assessment tools. During inspection the breaker is temporarily disconnected from the system by providing an alternate path for current. It is then made to operate forcibly and different quantities are recorded using portable test units. The acquired signal set is compared with the prerecorded reference set by personnel. Inferences on the breakers state are made based on this comparison. The data collected is used to predict the deterioration of the breaker and determine the time of next maintenance. This process is known as off-line monitoring as the breaker has to be taken off-line to perform the inspection. Off-line monitoring has two main drawbacks. First, the process is not very objective and may lead to inconsistency in conclusions and subsequent actions, due to difference in human judgement. Second, the inspection intervals are reported to vary widely, ranging from 5 weeks to 1 year and are also different for different tasks. The most frequent interval of inspection reported is 1 month. A large power system may have thousands of breakers and to inspect most of them so frequently proves to be an expensive affair.

Another method used to predict the state of the breaker uses a monitoring device attached to the breaker. Different physical and electrical quantities of the circuit breaker are measured and analyzed to detect anomalies in behavior. The analysis may be manual as in the previous strategy or may be automated using technologies such as expert systems or neural networks. This is known as online monitoring as the breaker is in service while it is being monitored. This methods allows the utility to perform just-in-time maintenance. In this strategy a maintenance team is kept on standby at all times. As soon as abnormality is reported the team is dispatched to perform maintenance. This method has low personnel costs, as frequent manual inspection is no longer required. However there are considerable equipment and installation costs. A large power system may have thousands of breakers causing equipment costs to outweigh the benefits achieved in terms of reliability and hence automated online monitoring has not found wide-scale acceptance.

Reliability centered maintenance

In this strategy maintenance requirements are established using probabilistic models and failure consequences and cost considerations. The procedure is complex and requires experience and judgement. It may be a long time before enough data is collected to create models that give accurate results. The failure rate of the breaker is calculated and maintenance intervals are scheduled accordingly.

A recent CIGRE survey [4] on the present and future maintenance practices by utility companies from different countries found the usage statistics to be as shown in Table II. The results of the survey indicate that utility companies are inclined towards using more of condition based and reliability centered maintenance. These methods when combined with automated monitoring offer increased breaker life at

Table II. Usage statistics for maintenance methods

Maintenance type	Current usage	Future usage
Time Based Maintenance	41%	24%
Condition Based Maintenance	38%	47%
Reliability Centered Maintenance	15%	24%
Other	6%	5%

lower maintenance costs by optimizing the maintenance procedures. The use of condition monitoring for breakers is evaluated on basis of the value added by the monitoring system against the cost of the installed equipment and the increased life-time of breaker. This thesis explores circuit breaker condition monitoring as a solution to improve reliability of breaker operation.

B. Problem definition

A circuit breaker is made up of many electromechanical parts. The main elements of a breaker are contacts, dielectric, operating mechanism, control circuit and casing. A fault in one or more of these elements may lead to failure of circuit breaker operation. Different monitoring systems have been designed and proposed to monitor the status of these elements and predict the time of maintenance. A group of researchers has developed a monitoring system that acquires information about the mechanism velocity, phase currents, gas pressure and temperature [5]. Another group here at Texas A&M university has developed a circuit breaker monitoring and analysis software which uses signal processing and expert systems to analyze the circuit breaker control circuit signals and diagnose abnormalities in the functioning of the circuit breaker [6]. Yet another group of researchers has designed a system for acquiring and analyzing vibration signals from a circuit breaker [7]. A report by CIGRE shows that approximately 25% of the major and minor failures of circuit breakers in service are caused by control circuit failures [8]. The main functions of the control circuit are

- Supervise the operating conditions of the circuit breaker
- Prevent operation if the circuit breaker is outside its operational capabilities
- Execute operating commands when it is safe to do so

Signals recorded from the control circuit can provide information about these functions and enable diagnosis of control circuit health.

Currently available monitoring systems are expensive and do not fully justify the cost of installing them. This thesis focuses on designing a solution to monitor the control circuit of a circuit breaker and gather data which can then be analyzed to predict maintenance time. The design of a monitoring system involves

- Determining the quantities to be measured
- Defining the functional requirements of the monitoring system
- Designing the architecture of the monitoring system
- Evaluating a prototype of the designed circuit breaker monitor

The designed system must cater specifically to measurement of the control circuit signals. The next section describes some of the existing monitoring solutions and their drawbacks.

C. Existing solution

Some of the data acquisition systems currently available in the market are listed in Table III. The systems listed do not cater specifically to measuring quantities from the control circuit. As a result they do not record enough information to make accurate diagnosis of control circuit faults. Most of the systems listed in Table III do not have sufficient number of channels to monitor all quantities required by the artificial intelligence tools to make good decisions about the status of the breaker. Some that have channels do not have the interfaces to take input signals of the voltage or current levels found in the circuit breaker control circuit. Some also require an invasive installation procedure thus increasing installation costs. Data collected from

Table III. Data acquisition systems available in market. Source: Refs. [9]-[14]

Product Name	Company Name	No. of channels	Bits per sample	GPS	Sampling Rate	Online	Wireless Transfer
BCM 200	Qualitrol corp	10	10	No	2kHz	Yes	No
CBT 400	Qualitrol corp	10	12	No	10kHz	No	No
SICAM AI16	Siemens	16	12	No	1kHz	Yes	No
Optimizer+	INCON	_	_	No	1.9kHz	Yes	No
TDR9000	Doble	3-24	_	No	10kHz	_	No
CBWatch-2	Areva	10	_	No	5kHz	Yes	No

circuit breakers all over the system can be combined to make deductions about the system configuration that help the network operators in increasing reliability. This application requires the data collected to be synchronized in time. Most systems do not have any option for time-synchronization of recorded data. With thousands to breakers to be monitored these limitations serve as a deterrent to the adaptation of online monitoring strategy on a large scale.

D. Proposed solution

Online monitoring of circuit breaker control circuit can be used to optimize the extent and timing of specific maintenance activities to be performed. The Circuit Breaker Monitor (CBM) proposed has the following features

- Low cost: The cost of CBM per breaker is less than $500
- Tailored interface: The input interface of the monitoring system is tailored to monitoring of circuit breaker related electrical quantities.

- Synchronized recording: The CBM synchronizes recorded data to a global time standard enabling system-wide applications to use the recorded data.
- Ease of installation: The circuit breaker monitoring system can be installed at a substation within minutes by one or two personnel. The system just need to be plugged into the signals and power to be usable.
- Cost of installation: Apart from the minimal labor cost no other cost is associated with equipment installation.
- Ease of use and maintenance: A simple graphical user interface allows the user to control the system and monitor the breaker.
- Data interface: The system provides centralized storage with a data interface upon which multiple applications can be built, thereby increasing utility of the system.

E. Conclusion

This chapter described the problem that the designed Circuit Breaker Monitor aims to solve. Maintenance methods currently in use by utility companies were discussed. The current status of solution was described and some of the existing research was discussed. A brief summary of the requirements for the proposed solution was presented.

CHAPTER II

CIRCUIT BREAKER THEORY

A. Definition of a circuit breaker

The ANSI/IEEE standard for definitions for power switchgear [15] defines a circuit breaker as "A mechanical switching device, capable of making, carrying, and breaking currents under normal circuit conditions and also, making and carrying for a specified time and breaking currents under specified abnormal circuit conditions such as those of short circuit." Circuit breakers are electromechanical devices made up of a number of components that work together to open and close the circuit on command. The main function of opening or closing the circuit is achieved by separating or joining a pair of contacts that are well insulated from the outside. The contacts serve as the connection point for the wires that enter and leave the breaker. The rest of the mechanism exists to facilitate the separation and joining procedures and to monitor them.

B. Functions of circuit breakers

Load flow control

During the normal operation of the power system, the power demand continuously keeps varying. The demand may become high in one area while becoming low in other. In order to generate and distribute power efficiently, power transmission from one region to other must be controlled. The circuit breakers are used to connect and disconnect transmission lines thus controlling flow of power in a certain direction. The flow of power can also be controlled by changing the magnitude and phase of the voltage. Circuit breakers are used to switch in and out devices like shunt reactors which are capable of changing the flow of power.

System protection

A huge system dispersed over a wide geographical area like a power system is vulnerable to faults. Circuit breakers are commanded to open during faults in order to protect the system equipment. Table IV lists the types of fault that can occur on a power system with overhead lines [16]. The breaker corresponding to the line on which fault occurs must open rapidly on fault in order to protect the system. Circuit breakers are incapable of detecting faults on their own. They are controlled by signals from other equipment like protection relays, SCADA, reclosers, etc. which are capable of detecting faults. A typical connection of circuit breaker and relay on a single ac line is shown in Fig. 1 [16]. The number 52 stands for the circuit breaker according to ANSI/IEEE device numbering system [17]. Upon a trip(open) signal from relay or SCADA, the circuit breaker must open very rapidly and break the current in the circuit. Today, network voltages are as high as 1000kV and the circuit breaker must be able to break current at these voltages within milliseconds. This is one of the most arduous functions performed by the circuit breaker.

Table IV. Types of transmission line faults

Fault type	Occurrence rate
single phase to ground	70-80%
phase to phase to ground	10-17%
phase to phase	8-10%
three phase	2-3%

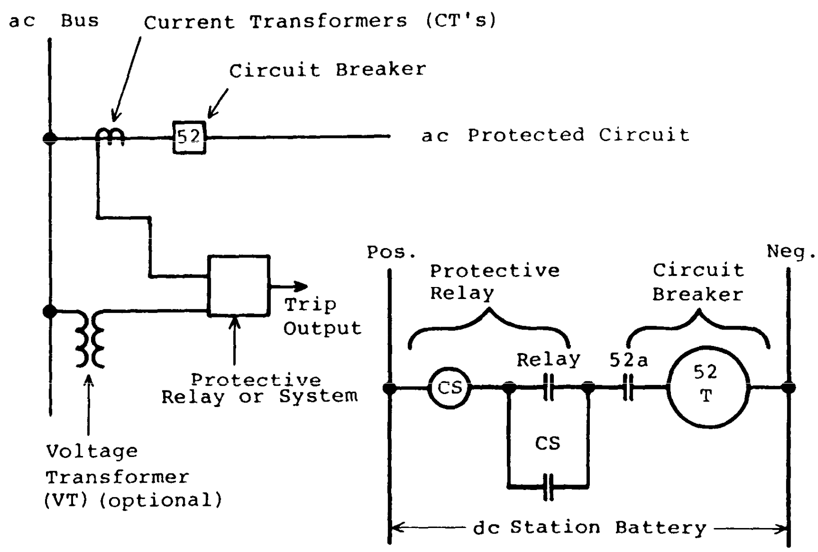


Fig. 1. Single line AC connections of protective relay and circuit breaker

C. Classification of circuit breakers

Circuit breakers are classified into different categories based on the voltage at which they operate, the installation method, the external design and the interrupting mediums [18]. Table V shows a brief list of different classes of circuit breakers. The classification shown in based on international standards ANSI C37.06 [19], C37.100 [15] and International Electrotechnical Commission (IEC) 62271-100 [20].

D. Circuit breaker control circuit

Control circuit description

Though circuit breakers have different designs and operating mechanism their control circuits contain similar elements. A simple schematic of circuit breaker control circuit with the most commonly found elements is shown in Fig. 2. The control circuit usually consists of two coils - a trip coil and a close coil. High voltage circuit breakers have an additional coil which serves as a backup trip coil. The circuit has

Table V. Classification of circuit breakers

Classification based on	Type	Description
Operation voltage	Low voltage	Rated for usage up to 1000 Volts
	High voltage	Rated for usage above 1000 Volts
Installation	Indoor	Designed for use only inside buildings or weather resistant enclosures
	Outdoor	Designed for use outside buildings
External design	Dead tank	The vessel surrounding and containing the interrupters and insulating medium is at ground potential
	Live tank	The vessel housing the interrupters is at a potential above ground
Interrupting medium	Air-magnetic	Air is the interrupting medium and the arc chute includes a magnetic blow-out coil
	Air/Gas blast	Air/Gas is blasted over the arc through a nozzle at high speeds (supersonic)
	Oil	Napthenic base petroleum oils form the interrupting medium
	SF_6	SF_6 a chemically stable, non-corrosive, non-flammable gas is used as the interrupting medium
	Vacuum	Vacuum breakers are used because of the exceptional dielectric characteristics and diffusion capabilities of vacuum

two inputs that control its function - Trip initiate and Close initiate. A high trip initiate signal results into a trip operation and a high close initiate signal results into a close operation. These signals are usually generated by the protection and control equipment like relay, SCADA, recloser etc. The control circuit is powered by a 130V DC source, usually a battery in the substation control house, called the supply voltage. All elements of the circuit are connected between the positive and the negative terminals of the supply voltage.Another voltage source called the Yard DC is used by most breakers to power the closing motor that charges the close coils (CC). The elements of the control circuit are described in Table VI [21].

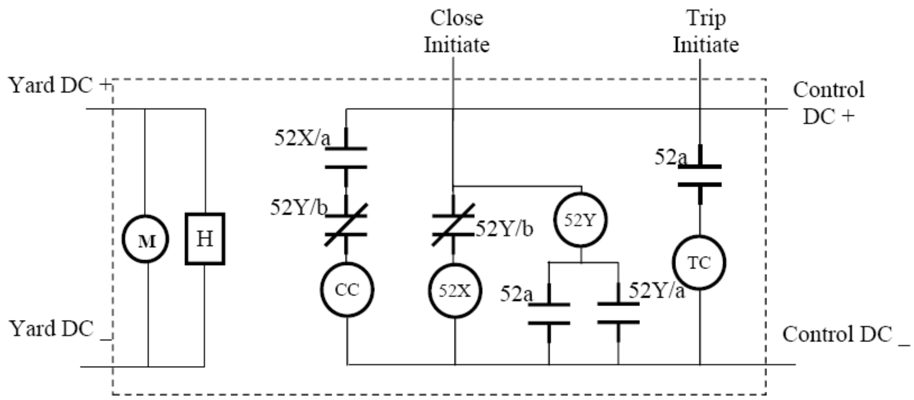


Fig. 2. Circuit breaker control circuit

Table VI. Elements of circuit breaker control circuit

Element	Definition
52a	This symbol represents and electrical switch in the breaker. It operates when the breaker mechanism changes state. It opens when the breaker opens and closes when the breaker closes. It is also called “a contact”
52b	This symbol represents and electrical switch in the breaker. It operates when the breaker mechanism changes state. It opens when the breaker closes and closes when the breaker opens. It is also called “b contact”
TC	TC stands for “Trip Coil”. The trip coil contains a plunger mechanism for opening the breaker. Its primary function is to open the breaker when energized
CC	CC stands for “Close Coil”. It is constructed similar to the trip coil. Its primary function is to open the breaker when energized
X coil	This is an auxiliary X relay that initiates the breaker close sequence. It represents a coil with a plunger mechanism for opening and closing contacts. When it operates, it changes the state of all contacts with 52X designation. Conversely, when it stops operating, all the contacts with 52X designation revert to their de-energized state
Y coil	This is an auxiliary Y relay that operates as an anti-pump mechanism to allow only one close operation for a single close initiate. It also changes the state of all contacts with 52Y designation
52Xa	This is a 52X contact which changes state when the 52X coil operates and enables the close coil to energize.
52Ya, 52Yb	These are 52Y contacts which change state when the 52Y coil operates and disables the closing sequence.

Relationship of signals to breaker health

The recorded signals from circuit breaker control circuit that provide information about the state of circuit breaker are known as "Performance indicators" [22]. The performance indicators for close and open operation are different are listed in Table VII. The trip and close initiate signals originate from the control house. A transition in these signals indicates the start of circuit breaker operation. Loss of these signals indicate a problem with the execution of relay sequence.

The control DC voltage provides power supply to the control circuit. A loss of this signal will impede breaker operation and indicates a problem with substation batteries which form the power source. The yard DC voltage provides power supply to the motor and heater as shown by M and H in Fig. 2. Usually the original source for yard DC is the same as control DC.

The 52a and 52b contact signals represent the voltage across auxiliary switches that specify the open or close status of the circuit breaker. The time difference between the transition of these two signals is inversely proportional to the velocity of CB operation. A deformation of these signals may indicate a dirty contact, a binding mechanism or a slow breaker.

The trip and close coil currents control the operating mechanism of the breaker.

Table VII. Performance indicators

Open operation	Close operation
Trip Initiate	Close Initiate
Control DC Voltage	Control DC Voltage
Yard DC Voltage	Yard DC Voltage
a Contact (52a)	a Contact (52a)
b Contact (52b)	b Contact (52b)
Trip Coil Current	Close Coil Current
Phase Currents	Phase Currents
	X Coil
	Y Coil

The movement of the operating mechanism is reflected in the current signals through the electromagnetic effect. When monitored these signals provide information about the operating mechanism.

The phase currents are not measured from the control circuit but they indicate the exact moment when the breaker makes or breaks the current and are used to check the consistency of other signals recorded from the control circuit.

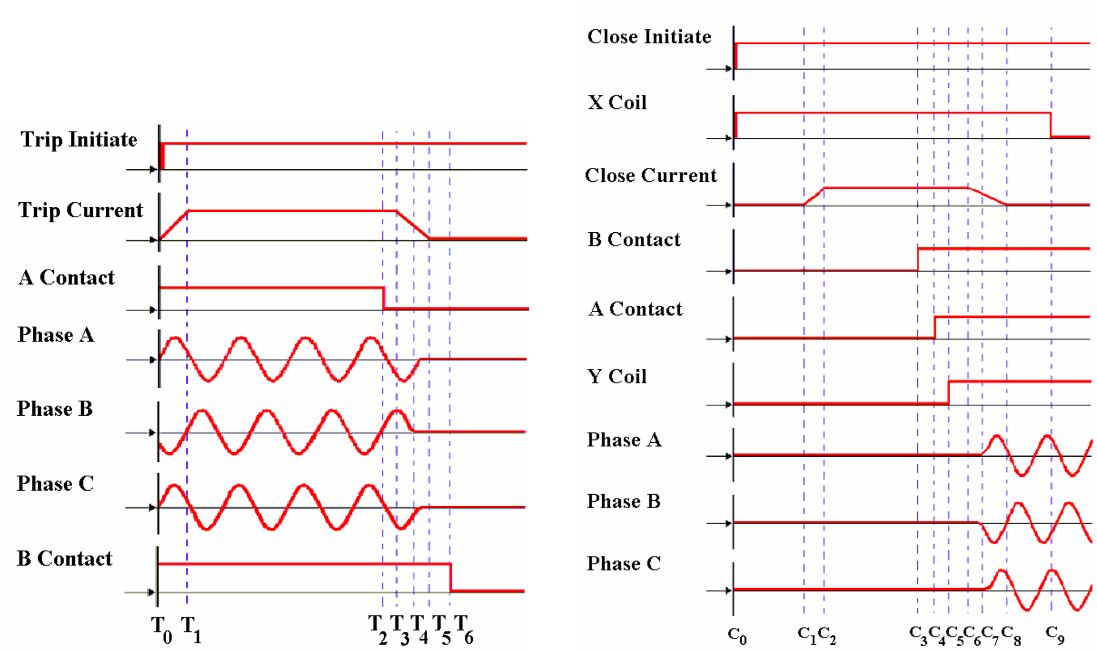
The X and Y coil signals prevent multiple close attempts in one close operation. Loss of these signals indicates a fault in the control circuit. The circuit breaker monitor should be designed to monitor these signals and store them for analysis to determine the health of the CB.

Control circuit operation

Breaker open operation

The circuit breaker is opened by separating the contacts and thus breaking the flow of current through them. In order to perform this function the control circuit has to go through a sequence of actions. The signals expected at different points in the control circuit during a trip event are shown in Fig. 3(a) [21]. Only seven signals that show a change in magnitude are displayed. The signals are ideal i.e. there is no instrumentation noise nor actual disturbances. It can be seen that upon trip initiate the trip coil current goes high. This initiates the plunger mechanism. When the breaker has opened completely this current comes back to zero and so do the phase currents since they cannot flow through an open circuit.

Fig. 3(a) shows different time instances labeled when transitions occur in the control circuit. It is assumed that before the open operation, the breaker is in closed position and functioning normally. At time T_0 the trip signal is asserted high by the



(a) Trip event and opening of breaker (b) Close event and closing of breaker

Fig. 3. Trip and close waveforms for circuit breaker control circuit

protection or control system. As the breaker is closed, so is contact 52a shown in Fig. 2, and the trip signal flows down to the trip coil (TC) and energizes it. The trip coil current ramps up and reaches its maximum value at time T_1. The breaker opening mechanism operates when the current has reached 70% of its maximum value. The operation of the breaker mechanism opens the 52a contact and the a contact signal makes a transition to zero at time T_2. When the 52a contact opens, the trip coil is disconnected from the asserted trip initiate and its current starts going down at T_3. The main interrupting contacts have separated by time T_4 and the phase currents go to zero as the line is open circuited. By time T_5 the trip coil current has ramped down to zero. As the breaker mechanism fully opens at time T_6, the b contact closes and its voltage goes to zero. The breaker is now open and remains in this state till a close initiate is received.

Breaker close operation

The circuit breaker is closed by bringing the main interrupting contacts back together. This operation starts when the close initiate signal is received from the protection relays, reclosers or SCADA. The signals expected during a close operation are shown in Fig. 3(b) [21]. It can be seen that 9 signals undergo transition during a close operation. Different time instances when transitions occur are labeled in the figure. The breaker is assumed to be in open state initially. At time C_0, the close initiate signal is asserted. The close signal propagates to the 52Yb contact which is in closed position as the Y coil is deenergized. The signal thus propagates further to the X coil, shown as 52X in Fig.2. The X coil is activated and the X coil signal makes a transition to high. The operation of X coil causes the 52X contact to close. Upon closing of 52X contact, a path is established from positive terminal of control DC source to the close coil. The close coil is energized and the close coil current starts increasing at point C_1. At point C_2, the close current reaches its maximum value and the close operation is initiated.

As the breaker close operation proceeds, all 52b contacts are opened and all 52a contacts are closed. This can be seen in Fig. 3(b) as the b contact and a contact make transitions at times C_3 and C_4 respectively. When the 52a contact closes, it activates the 52Y coil and 52Ya and 52Yb contacts change state at time C_5. The 52Yb contact opens thereby deenergizing the close coil and close coil current begins to ramp down at C_6. The main interrupting contacts have established connection by time C_7 and phase currents start flowing at this point. At time C_8 the close current has completely ramped down to zero. The opening of 52Yb contact also disconnects the 52X coil from positive DC voltage and deactivates it. The X coil signal makes a transition to zero at time C_9.

The Y coil that was initialized at $C_5$when the 52a contacts closed at C_4, stays energized as long as the close signal is high, preventing a reclosing of the breaker when the close signal is high. To close the breaker again, the close initiate signal must be reasserted by taking it low and then bringing it to high voltage again. The Y coil is also called "Anti-pump coil" as it allows only one close operation per close initiate signal. The transition order described in the above sections is just a typical case and the actual order may be different for different breakers under normal operation.

In summary, one can establish the fact that the breaker opened correctly on not by looking at the timing sequences and the signal levels.

E. Conclusion

This chapter presented the definition of circuit breaker and its main functions. It described the different classifications of circuit breakers based on industrial standards. It discussed the control circuit of the circuit breaker and its electrical characteristics. The close and open operation of the breaker were described in terms of the control circuit signal transitions. Relationship between breaker health and sequence of control circuit signal changes was discussed.

CHAPTER III

MONITORING REQUIREMENTS

A. Introduction

The first step in designing a solution is to define the functional requirements of the system. The monitoring system requirements were generated after consulting with industry members and are based on the circuit breakers and other equipment already in use by Center Point Energy. The two main functions which the circuit breaker monitoring system should be designed to perform are

- Data acquisition: The input signals must be captured and converted to digital form for analysis and storage.
- Analysis and storage: The data gathered by acquisition units at breaker must be collected at a central location, preprocessed and stored for further analysis.

The requirements for these two functions are different and independent of each other in case of a modular implementation. This chapter describes the function requirements of the monitoring system and tries to explain the logic behind the choices made.

B. Data acquisition requirements

Electrical characteristics of input

The data acquisition unit must acquire signals from the circuit breaker control circuit discussed in section D of Chapter II. The electrical characteristics of the signals to be monitored are listed in Table VIII. The signals can be classified into three groups

Table VIII. Circuit breaker control circuit signals

Signal Name	Analog(A)/ Status(S)	Nominal Range	Function
		VOLTAGES	
Control Voltage	A	125V± 15V	Provides Pos/Neg voltage for contacts
Light Wire	A	125V± 15V	ON/OFF Indicator
Aux. Contact B	A	125V± 15V	Establishes connection from Light to Neg
Yard DC	A	125V± 15V	Runs CB motor
Aux. Contact A	A	125V± 15V	Indicates breaker status
		CURRENTS	
Close Coil Current	A	< 10	Used to physically close the CB
Trip 1 Coil Current	A	<10A	Used to physically open the CB
Trip 2 Coil Current	A	<10A	Used to physically open the CB
Phase A Current	A	5A	Indicates breaker status
Phase B Current	A	5A	Indicates breaker status
Phase C Current	A	5A	Indicates breaker status
		EVENTS	
Close Initiate	S	125V± 15V	Initiates a close operation
Trip Initiate	S	125V± 15V	Initiates a trip operation
X Coil	S	125V± 15V	Closes all 52X contacts, Establishes a path from POS to 52CC
Y Coil	S	125V± 15V	Opens all 52Y contacts, Interrupts 52CC and X coil currents

1. Voltage signals: These signals consist of voltage measurements at different points in the control circuit. The nominal range of voltage signals is 125±15V. These signals need to be recorded as analog signals and then converted to digital form.

2. Current signals: These measure the currents through sub-circuits of the control circuit. The nominal range of current signals is 10A. These signals can be recorded as voltage signals taken across the shunts in the control circuit. Current signals are also measured from the current transformers set up on the three phases of transmission line entering the breaker. The phase current signals are in the range of 5A during normal operation of power system. These signals can

be tapped as voltage signals across shunts connected on the secondary of the CTs. These signals also need to be converted to digital form for storage and analysis.

3. Event signals: These signals are status signals i.e. their high or low status indicates the state of the circuit breaker operation. The signals can be in two voltage states [0V, 125V]. Though the signals are only status signals, small variations in their voltage levels contain important information about the functioning of circuit breaker. The signals must thus be recorded as analog signals to capture even the small variations.

Input processing

Signal conditioning

The input signals discussed above must be scaled appropriately for converting them into digital form for processing and storage. Most analog to digital conversion circuits require the input signals to be in the ± 10V or ± 5V range. A signal conditioning circuit must scale the signals listed in Table VIII to be in the range required by the A/D converter.

Galvanic isolation

The digital equipment works at low voltages and is sensitive enough to be damaged by the voltages higher than 20V. Faults in the system may cause input voltages to fluctuate resulting in damage to the monitoring equipment. The digital equipment should therefore be galvanically isolated from the analog input signals. Fig. 4 shows the required functionality of signal conditioning and galvanic isolation graphically.

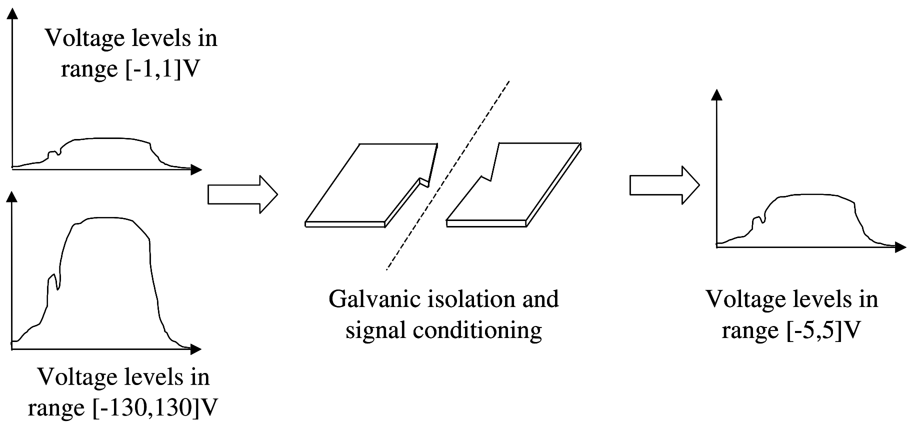


Fig. 4. Signal conditioning and galvanic isolation

A/D conversion

The analog signals must be converted to digital form with a resolution high enough to allow for accurate analysis. It is observed that a resolution of 12 bits for the $\pm$5V range is sufficient for required analysis accuracy. The analog signals are sampled and discretized at different time instances for conversion to digital form. The sampling rate provided by the A/D converter must be high enough to allow for accurate reconstruction of signals for analysis. It was determined that a sampling rate of up to 10kHz was sufficient for most applications. Fig. 5 shows the process of analog to digital conversion. All signals must be sampled synchronously and then converted to digital form. The signals listed in Table VIII vary from breaker to breaker and hence the input conversion circuitry must have enough number of channels to monitor all required signals.

Synchronization

The data recorded at different circuit breakers in the substation must be synchronized in time in order for the analysis software to draw conclusions about the functioning of

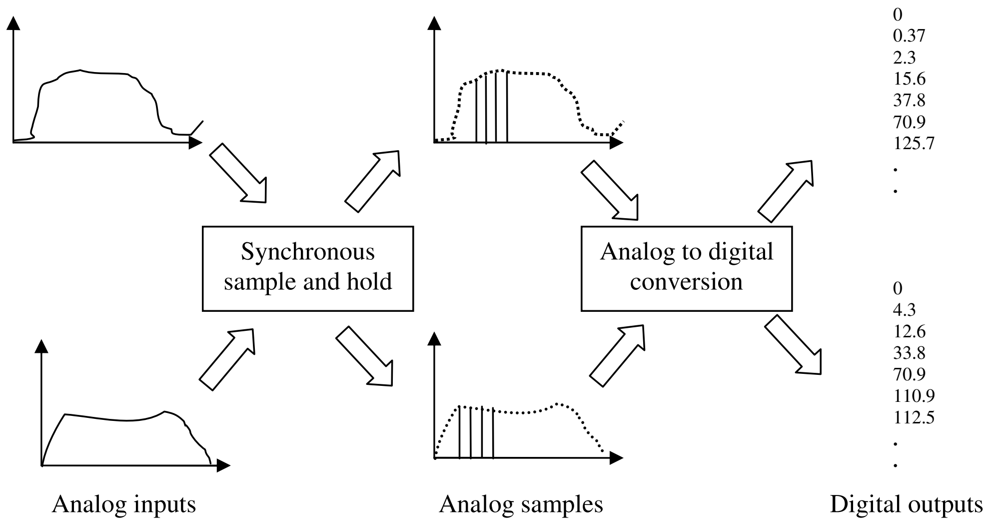


Fig. 5. Analog to digital conversion

the system. For example, in a breaker and half configuration, two lines are protected by 3 breakers and two breakers must be opened to disconnect a faulty line from rest of the substation. Unless the data recorded from these to breakers in synchronized in time, accurate deductions about the abnormalities in line opening cannot be made. Time synchronized data may also be used for different applications which analyze the working of the entire power system. Data must therefore be synchronized to a universal time system. A GPS time system is ideal for this purpose. The records obtained must be time-stamped with GPS time. Most applications can work with data sampled at less than 10KHz. The maximum synchronization required is therefore 1/10Khz = 100 microseconds. The GPS hardware and the algorithm used for synchronization should be able to provide an accuracy of at least $100\mu s$.

Data transmission

The data recorded at the circuit breakers must be transmitted to the central storage location. The cost for wired vs. wireless transmission of data were investigated.

The wireless transmission solution was found to be more cost effective and easy to implement [23]. If the data acquisition system was to be set up at each breaker of the entire power system, it would be very expensive to lay out the wires to connect the units to a central location in the substation.

The wireless transmission system chosen should enable data transfer from multiple points to the central storage system. The bandwidth required for real time data transfer of 15 signals, sampled at 2KHz is determined as 576 Kbps. Different wireless technologies viz. FDMA, TDMA, Spread spectrum, CDMA etc. were investigated. The criteria for selecting the wireless technology are shown in Table IX. The only technology that fits the requirements is spread spectrum wireless technology.

System control

The user should be able to control CBM operation and configure it for optimum performance. The CBM should have a user interface which allows the user to set different data acquisition parameters like sampling frequency, recording duration, number of channels to be recorded. The user should be able to select channels which provide information about trip and close events. User should be able to start and stop the CBM system as required. User should also be able to receive notifications when events have occurred and data is being recorded.

Table IX. Criteria for selection of wireless technology

Property	Desired value
Data rate	600Kbps
Distance	250m (avg)
Points of communication	15
Power	milliWatt range

C. Data storage and analysis requirements

Storage

The data is collected and stored in digital form. Storage of data from all breakers over the substation requires that the digital storage media must have sufficient storage space. A record for an event for an event that lasts for the duration of 1 second is approximately 200kB in size when the sampling is performed at 5kHz. Assuming 12 breakers providing one record every hour, the storage size required to store one month of data will be 12 breakers x 24 hours x 30 days x 200kB = 172800kB $\approx$ 1.65 GB. Month long data may be maintained on the main storage while old records are compressed and archived on secondary media. The criteria for selection of a storage medium are listed in Table X. There are different format in which digital data can be stored on storage media. The acquisition software must be able to store data in a format that can be recognized by most applications that will use the data. The COMTRADE file format is an industry wide standard and should be used for data in the storage [24]. A database of the stored files may be maintained for ease of retrieval and use by applications.

Table X. Criteria for selection of storage technology

Parameter	Primary storage	Secondary storage
Storage space	2GB	24-240GB
Access time	μs range	few minutes
Reliability	High	High
Access type	Random required	Sequential is ok

Analysis reports

The analysis application must be able to take input data in digital format and process it. It should implement a method to keep track of incoming data and its storage location. It should be able to access the data on command from user and process it fast. It should allow the user to perform analysis operations through an interface and present analysis results through the same interface. The analysis operations to be performed include - detection of events and signal processing of recorded data to check for abnormalities. The application must generate reports which inform the user of these abnormalities. The analysis application should be able to inform the user of events that occur on the system through a graphical interface. The analysis software should be able to display the data acquired an stored as waveforms on demand. It should also enable the user to view a log of events that have occurred in the substation in past.

D. Conclusions

This chapter identifies the requirements for the CBM design. The requirements are generated based on the functions that the CBM needs to perform. These requirements form the basis of the design for the solution discussed in Chapter V. The architecture of the hardware and software designed for the monitoring system is discussed in the next chapter.

CHAPTER IV

SYSTEM ARCHITECTURE

A. Introduction

This chapter describes the over-all architecture of the circuit breaker monitoring system. The system design is modular in nature to allow for re-usability of hardware and software blocks. The requirements described in previous chapter specify that the data acquisition unit must be mounted on the breaker. One data acquisition unit and processing unit is required for each breaker. In order to reduce the total cost of the system a master-slave architecture is proposed which keeps the data acquisition hardware at the breaker, called the slave, to the bare minimum and combines the processing for all breakers into one processor unit, called the master.

In the master-slave architecture, the slave units are set up at each breaker in the switchyard and are hardwired to acquire the signal data. The master unit is set up at the control house to gather the data collected by all slave units and process it. Fig. 6 shows the architecture of the CBM system within a substation. The system is designed to allow for as many slaves as there are circuit breakers in the substation. The slave systems can be controlled from the control house using the interface provided by the master system.

B. Hardware architecture

The hardware is designed to provide an inexpensive solution for monitoring data accurately. It consists of slave systems mounted near the circuit breakers in weather proof enclosures. The master unit is placed inside the control house which has controlled environment for continuous operation of master unit within normal parameters. The

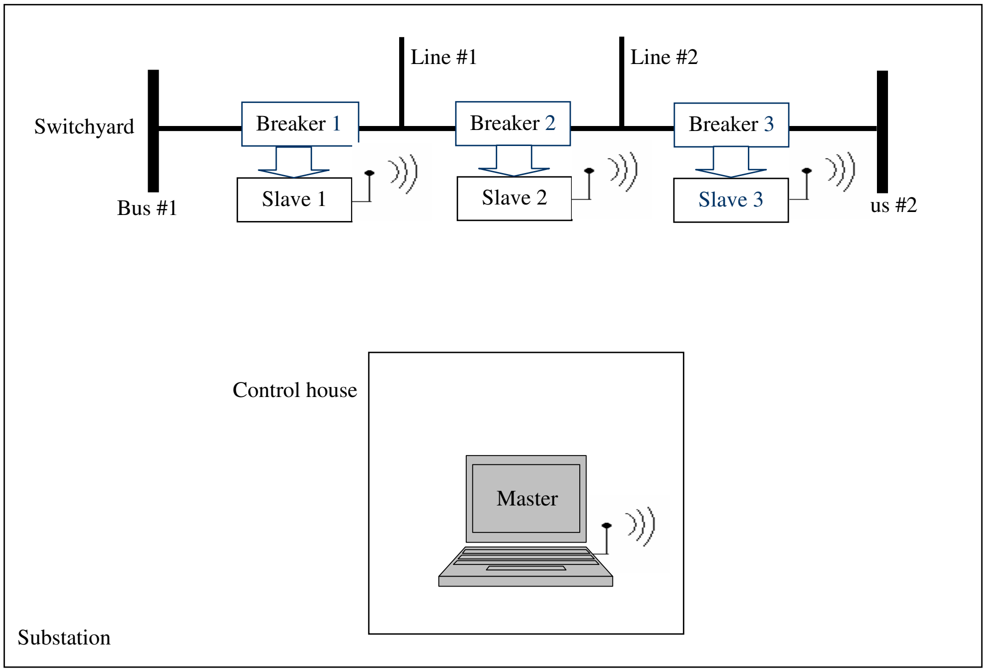


Fig. 6. Architecture of monitoring system

units communicate to each other using wireless communication.Fig. 7 shows the overall block diagram of the hardware design.

Slave unit architecture

A low cost solution for monitoring makes it imperative that the slave units that perform data acquisition at each breaker be stripped down to the bare essentials. Thus the slave unit is designed only to acquire data signals and transmit them to the master unit without performing any resource intensive processing on the signals. The slave unit consists of 4 important components - signal conditioning, analog to digital conversion, processing and wireless transmission. Fig. 8 shows the block diagram of the slave system.

1. Signal conditioning module: The signal conditioning and isolation module provides appropriate voltage levels for data acquisition. The signals of the circuit

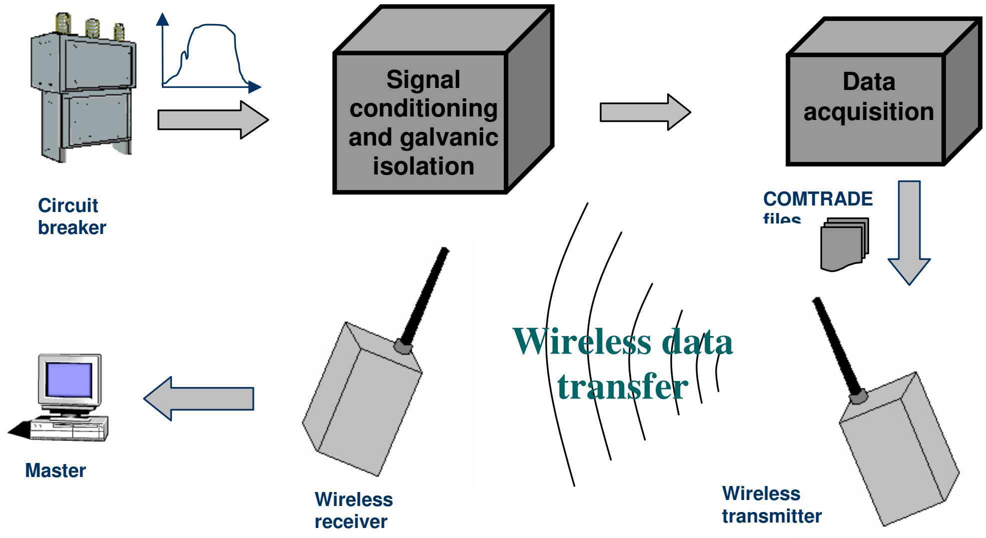


Fig. 7. Block diagram of monitoring system hardware

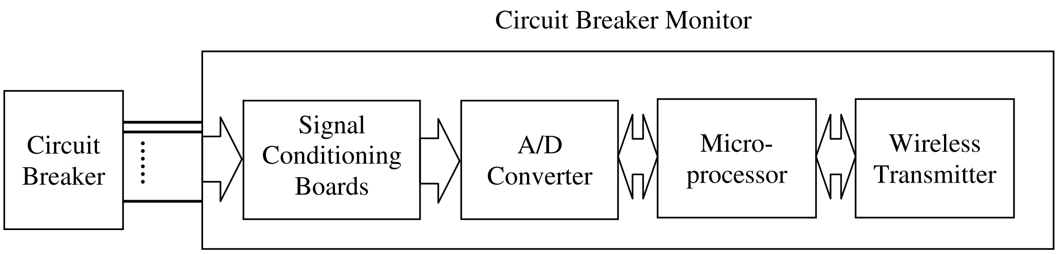


Fig. 8. Block diagram of data acquisition system

breaker control circuit are at two voltage levels. The status signals are at 130V DC where as the shunt signals which monitor currents are in the $\pm$1V range. The signal conditioning module scales the input signals to be in the [-5, +5]V range as required at the input of the A/D converter module. The architecture of the signal conditioning module is so designed that the high or low voltage input signals are first reduced or amplified in magnitude. The circuit provides selectable gain modules to achieve this. The signals are then passed through an isolation block. The signals at the output of the isolation block cannot exceed

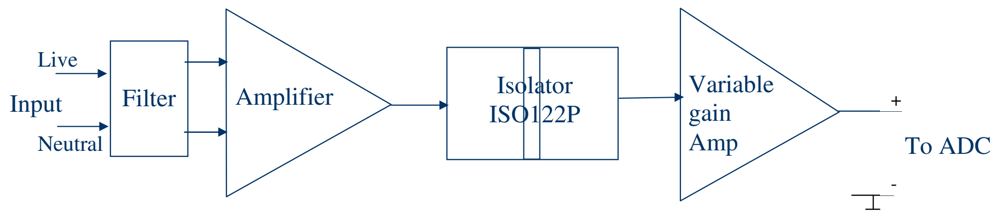


Fig. 9. Architecture of signal conditioning module

±15V irrespective of the input signal values. After isolation the signals are passed through a adjustable gain module, which allows fine tuning of the gain to get the desired overall gain for each signal. Fig. 9 shows the architecture of signal conditioning board .

2. Analog to digital conversion module: The A/D module takes the input signal in [-5, +5] volt range and converts it to a digital signal. The module should provides a resolution of minimum 12 bits for the voltage range. The sampling is performed synchronously for all channels. The sampling rate can be set by the user within the available range of the hardware. The module is connected to the processor and transfers data to it and receives control commands from it.

3. Microprocessor: The signal output from the A/D module acts as the input for microprocessor module. The microprocessor formats and temporarily stores the recorded data in its storage area. It controls the data acquisition according to the user specified parameters. The microprocessor is also connected to the wireless communication module. It receives command messages from the master unit through the wireless communication module and transmits recorded data back to the master through the same module. It also receives GPS synchronization signals from the master unit and synchronizes the recording accordingly.

4. Wireless Transceiver : A wireless modem employing Frequency Hopping Spread Spectrum technology is used to transmit the collected data to the master unit in the control house. Frequency hopping spread spectrum technology is chosen because the transmission range required in a substation can only be achieved using this wireless technology. The modem works in a point-to-multipoint mode. In this mode, the slave units communicate with the master unit and vice versa but there is no communication between the slaves. In this mode the slave to master data link is usually strong, ensuring reliability of data transfer. The wireless module acts as one of the multipoint nodes and communicates with the master unit. The communication is controlled by the microprocessor which programs the wireless transceiver for asynchronous transmission so that messages can be sent and received as and when event happen.

All four components of the slave architecture are integrated to work together and their functioning is controlled by the software operating on the processor.

Master unit architecture

Only one master unit is installed per substation. The master unit gathers data from all slave units through wireless communication and must be designed to have a bandwidth high enough to sustain data transfer without any loss. The system is designed in a modular fashion so that if one module fails it can be replaced by another module providing a similar interface without changing other modules. Fig. 10 shows the functional block diagram of the master unit. The system consists of four main components.

1. Wireless transceiver: The transceiver is identical to that used in the slave module and uses Frequency Hopping Spread Spectrum technology for wireless com-

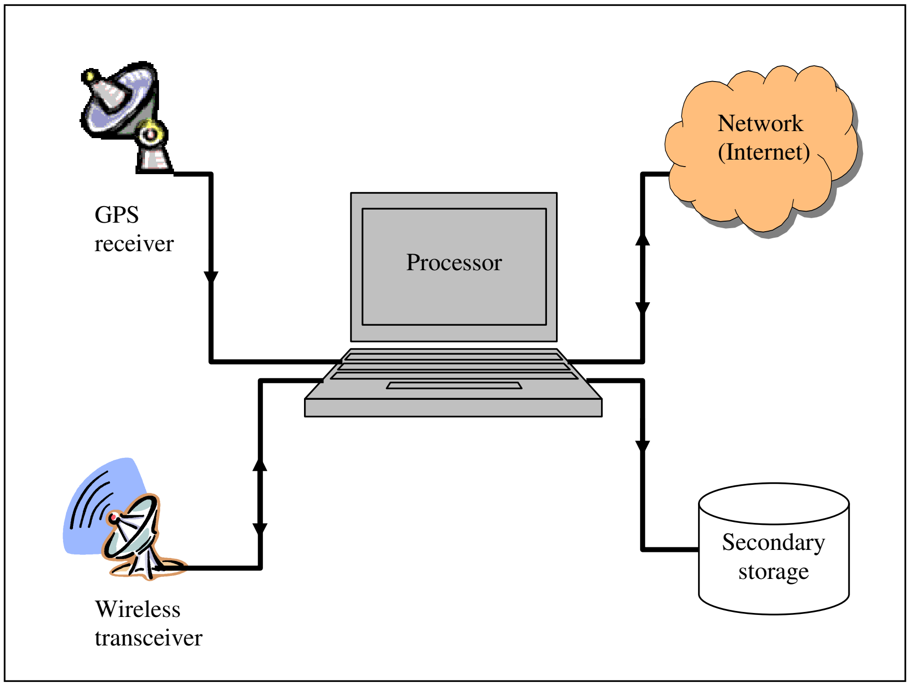


Fig. 10. Functional block diagram of master unit

munication. It works in the point-to-multipoint mode and acts as the master node. It is connected to the processor module which controls the communication protocols.

2. Processor: The master unit has a processor module to process incoming data and control the functioning of the data acquisition system. The processor is connected to two devices. One device is a wireless transceiver which allows it to communicate with the slave units and acquire the data recorded by them. Another device is a GPS receiver which provides it with accurate time signals. The processor may also be connected to a network, like internet to allow operators to remotely control the monitoring system and gather data at a central location. The processor executes a graphical user interface locally which allows the user to set and control the system. For this purpose, it has an operating

system, graphical display device and an input device attached to it.

3. Storage: The system has two types of storage. The primary storage as defined in Chapter III is internal to the processor module. It enables rapid access to the data required by applications executed on the processor. The secondary storage system as shown in Fig. 10 is external to the processor module. It may be connected or disconnected from the processor module as required. Data is periodically transferred from primary storage to the secondary storage device for archival.

4. GPS receiver: A GPS receiver is used to receive GPS clock signals from GPS satellites. The receiver is connected to the processor unit. The clock signal is received by the processor and its clock is synchronized to the GPS signal by the control software. The signal is used to also synchronize all the slave units using a network time synchronization algorithm described in Chapter V.

The integrated master system is controlled by the software described in the next section.

C. Software architecture

The circuit breaker monitoring system is event driven i.e. the signals are recorded when an event occurs and recording parameters are changed on user command. The software is designed to identify events and then perform the desired actions. The software chosen for both systems depends on the ability of the processors to execute it and also the cost of the compiler and base operating system.

Slave unit software

The slave unit software should performs the following functions

- Control data acquisition parameters of the A/D converter namely sampling frequency, input range and record duration.
- Detect events and record data for specified duration in memory.
- Transmit data to master unit.
- Receive commands from master unit and execute them on slave unit.

The software is broken down into modules for ease of programming and testing. The modules integrate together to form the complete system software. Fig. 11 shows the architecture of the slave unit software.

A/D conversion module

This module controls the A/D conversion of the input signals collected from circuit breaker control circuit. It sets the frequency of sampling the signals and the scaling factors for the digital signals. It must trigger the command execution module whenever new data is available. Upon order from the command execution module, it must transfer converted data directly to the data storage module. This routine is executed maximum number of times by the slave unit processor.

Data storage module

The data storage module takes data from A/D conversion module and stores it in available memory locations in the processors secondary memory (flash memory). This is done to reduce cost of the slave processor as primary memory (RAM) is expensive. Only a minimum of primary RAM as required by the operating system and software

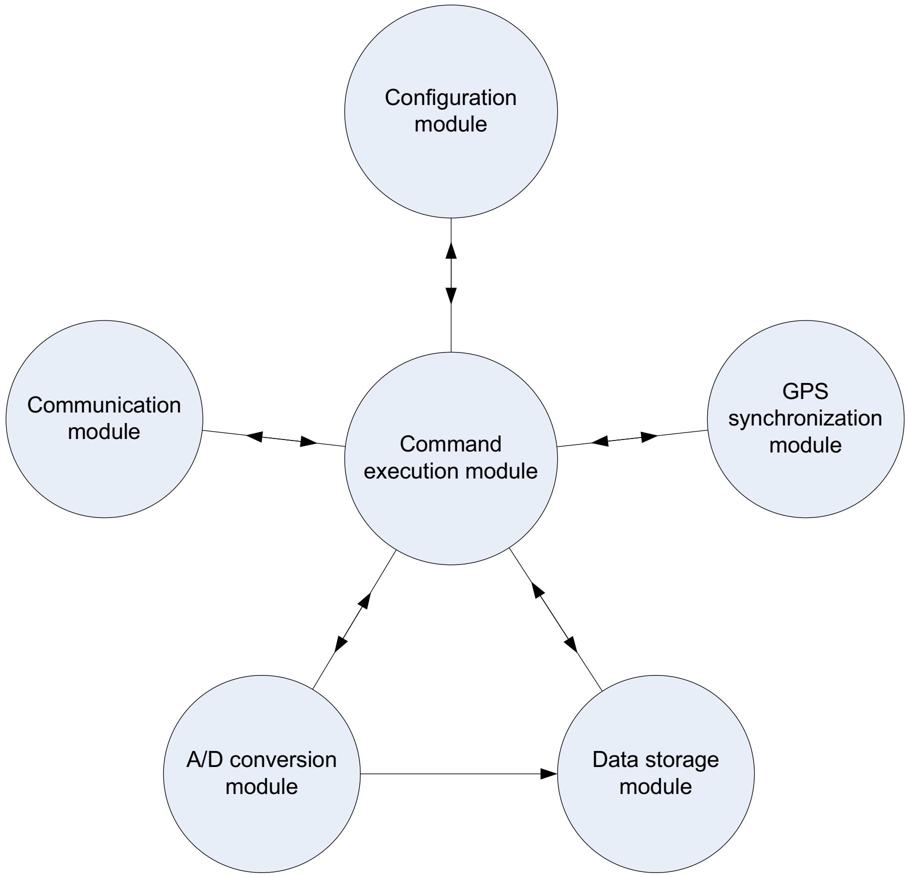


Fig. 11. Architecture of slave unit software

is used. 2MB of memory is sufficient for a basic operating system and slave unit software. The storage module must ask for memory resources from the processor and upon allocation of resources transfer data to the appropriate memory locations. Memory resource should be enough to store data from at least 5 events recorded at 5kHz. When no memory resources are available it must stop the data acquisition process and notify master unit of lack of memory.

Communication module

This module runs the communication protocol between the slave and master unit. Whenever a command is received from the master unit, processing is stopped and control goes to the communication module. All commands received from the master unit are parsed and then control is handed back to the command execution module with command information. This module also provides the command execution module with an interface to transfer data to and from the master unit.

Configuration module

This module initializes the data acquisition hardware and makes it ready to record data. It sets all the required hardware parameters. It also re-configures the hardware whenever a configuration change request is received from the master unit.

GPS synchronization module

The GPS synchronization module uses a network synchronization algorithm to synchronize the slave units time with the master unit. It can send and receive time stamps to and from the master to accomplish this goal. It periodically requests the master unit for accurate time stamps and then using the algorithm synchronizes the slave unit clock with the master unit clock.

Command execution module

The command execution module is the brain of the system. It prioritizes the tasks that a slave unit must perform. Since the slave unit does not have a pre-emptible processor, two threads cannot run simultaneously. When the A/D conversion routine is working, the GPS routines must be put on hold. The command execution module is responsible for controlling the flow of the slave system algorithm. It must detect events when they happen and activate the appropriate routine to perform required action.

Master unit software

The master unit software performs the following functions

1. Allows user to control the slave unit
2. Gathers data from all slave units and stores it
3. Detects events and allows the user to view waveforms and event logs
4. Provides an easily accessible data interface for other applications

The master units software is also event driven like the slave unit software. It handles two types of events - those generated by the user and those generated by the slave unit. Events generated by the user include configuring or restarting the slave unit and viewing the acquired data. Those generated by the slave unit include data transfer, configuration transfer and GPS synchronization. Fig.12 shows the different modules of the master unit software that handle these events.

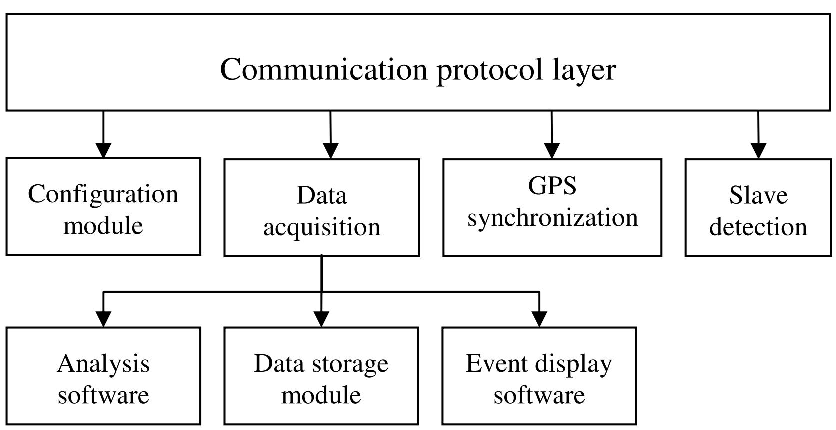


Fig. 12. Architecture of master unit software

Communication protocol layer

This layer handles all the communication between the master and slave unit. All modules that need to talk to the slave unit can do so through the communication layer. It implements a communication protocol which can be understood by its counterpart on the slave unit. The configuration, data acquisition, slave detection and GPS synchronization modules execute all their communication requirements through this layer. The layer should provide with an interface which is independent of other master unit software algorithms so that the communication protocol doesn't have to be changed even if the master unit software application changes.

Configuration module

This module allows the user to view the configuration of the slave unit. It displays the slave unit parameters on the graphical user interface and allows the user to change them. When some parameters are changed, the configuration module commands the slave unit to change these parameters using the communication layer to transfer the new configuration.

Data acquisition module

Whenever an event happens on the slave unit, it sends a message to the master unit that it is ready to transmit data. The communication protocol layer upon receiving such a message activates the data acquisition module. It works with the communication layer to receive all the data recorded by the slave unit and stores it in a standard format in the local storage medium through the data storage module. When data transfer is complete it notifies the user of the new event and allows him to view the data received through the event display software. If certain specific events have occurred that require analysis, it triggers the analysis softwares available through the analysis software module.

GPS synchronization module

This module controls the synchronization of the master unit to the GPS clock. It also responds to the slave units requests for synchronization and send accurate time data to it. The module receives GPS signal from the GPS receiver attached to the processor and interprets it to get the accurate time. It then sets the master unit clock to that time. It gets periodic requests from the slave unit for time signals and sends time signals accordingly through the communication layer.

Slave detection module

When a system is started the slave detection module probes each slave unit set up in the substation, using the communication layer, to detect if its is working or not. Inactive devices are flagged as erroneous and an error alarm is displayed to the user. The user can also execute the detection process when the system is functioning to get the status of all slave units in the system.

D. Conclusions

This chapter described the architecture of the Circuit Breaker Monitoring System. A master-slave architecture is proposed which will keep the cost of the system per breaker to a minimum. The different components of the slave and master hardware are described and their interconnection details are presented. The software requirements for the slave and master system are defined and their component modules are described in detail. The design described in this chapter is generic in nature. The next chapter describes a specific implementation of the design.

CHAPTER V

SYSTEM IMPLEMENTATION

A. Introduction

The previous chapter described the generic architecture of the system that can satisfy the functional requirements of the circuit breaker monitoring system. This chapter describes the implementation of a working prototype to meet the constraints specified in previous chapters. The development of the Circuit Breaker Monitoring System is an ongoing process at the Electric Power and Power Engineering(EPPE) labs in Texas A&M university. The implementation of first prototype of the monitoring system and the design of the software intended for the second prototype is described in this chapter. The implementation of second prototype is underway at the time of writing of this report.

The implementation can be broadly classified into two categories for ease of description. One category is hardware which describes all the electronics that went into the system and another is software which describes the control instructions written to make the hardware perform the desired task. The hardware design is very similar in both the first and second prototype, the only difference being that the second prototype uses low cost components offering almost the same functionality as the first prototype. This chapter describes the hardware designed for the first prototype.

The software designed for the first prototype is a very rudimentary one. It only provides a command line interface to execute data accusation functions. No interface is available to change the configuration of the device or to view the acquired data. The first version of software was developed with the intention to test the working of the prototype in the field and then to make the required modifications in the second version to meet the functional requirements. This chapter describes the design of second version of the software with the modifications incorporated.

B. Hardware

The system hardware can be divided into slave unit hardware and master unit hardware. These two sets of hardware are physically separate from each other. They however depend on each other to perform the data acquisition and hence must use consistent technology. The next two sections describe the slave and the master unit hardware.

Slave unit hardware

The slave unit hardware consists of 5 modules integrated together, signal conditioning module, processor, flash storage, wireless transceiver and power supply.

Signal conditioning module

The signal condition module is designed with discrete components mounted on a PCB to provide filtering, isolation and appropriate gain for the input signals. The schematic of the signal conditioning circuit is shown in Fig. 13. The schematic displays the circuit used for one channel. The circuit is replicated as many times on the PCB as the number of required channels.

The circuit can be divided into three parts according to the function each performs. First part is integrated circuit U1 with external resistors, capacitors and inductors. Inductors L1 and L2, and capacitors C1 and C2 are used to perform noise filtering. Integrated circuit U1 is operational amplifier which, with external resistors serves as an instrumentation amplifier. Its purpose is to perform signal conditioning.

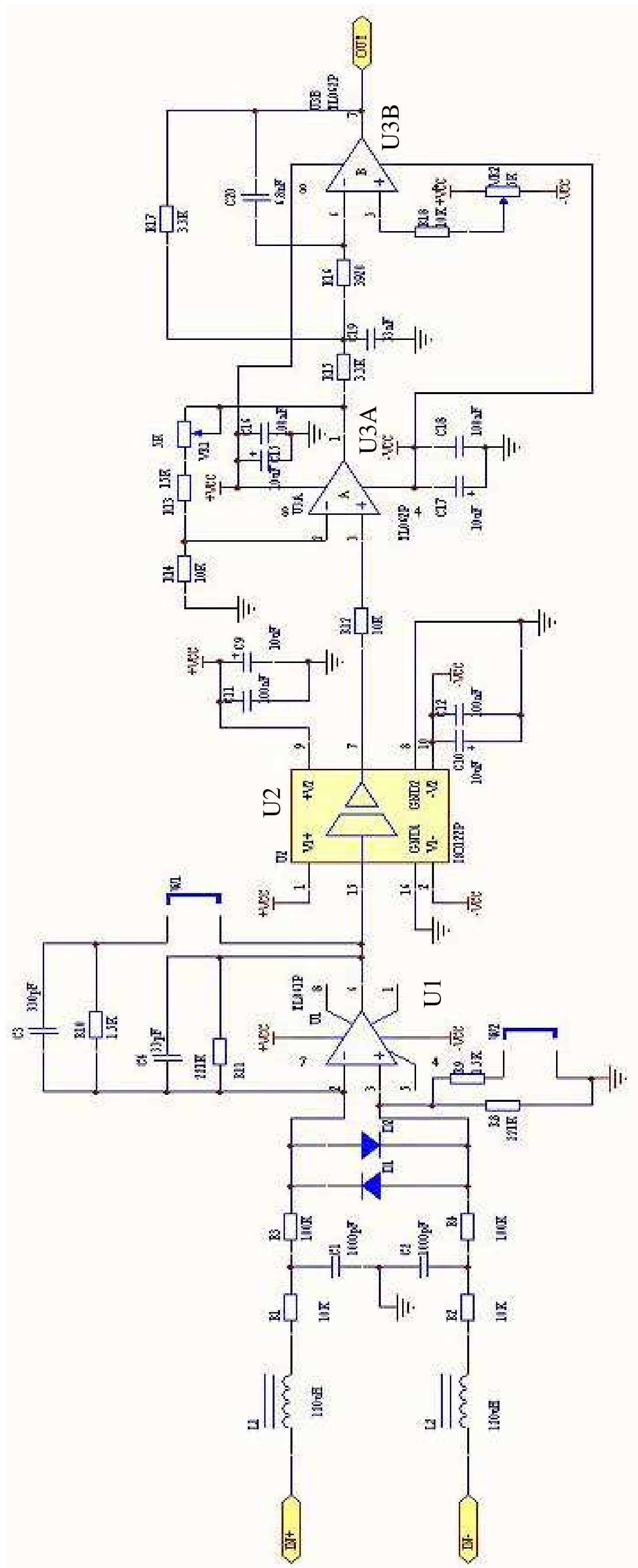


Fig. 13.: Schematic diagram of signal conditioning circuit

The circuit is designed so that it can provide two different levels of gains for voltage signals and current signals. Values of the resistors R8, R9, R10 and R11 are calculated for the desired gain. The gain can be set to low or high by connecting or disconnecting the jumpers W1 and W2 respectively. The low gain is required for high voltage signals where as high gain is required for shunt signals. The gain is set to 0.015 for high voltage signals and 2 for the low voltage shunt signals.

The second part is IC U2 the isolation amplifier ISO122P manufactured by Texas Instruments which provides galvanic isolation between the input signal and circuit output. The ISO122p IC works by internally generating a high frequency signal to modulate the input signal. The signal is demodulated at the output to generated the original signal waveform.

The third part is IC U3 combined with discrete components. It performs output filtering and provides additional gain so that output signal has voltage level of 5V if input signal is 130V. The IC consists of two operational amplifiers. Amplifier one provides a finely adjustable gain from 2.5X to 3X allowing the user to adjust level of the output signal. The other operational amplifier with external components (resistors and capacitors) forms a 2-pole low-pass filter with cut-off frequency at approximately 1.8 kHz. Potentiometer VR_1 allows for fine adjustment of output signal in the range of 5V, while VR_2 is there to allow elimination of DC offset.

Processor and storage

A 80486 architecture based processor running a ROM-DOS operating system is used as the main processing device. A 32Mb flash memory chip installed on the processor board serves as the storage device for the recorded data. The processor has a 50 pin bus for communicating with the A/D board. The processor also has two serial ports, one of which is used for communication with the master unit.

Wireless transceiver

A wireless transceiver manufactured by FreeWave technologies is connected to the serial port of the processor. It communicates with the master transceiver unit using Frequency Hopping Spread Spectrum technology. The transceiver is set to operate as a slave in the point-to-multipoint mode of operation. The data rate is set at 115,200 Bps.

Master unit hardware

The master unit hardware must be able perform data analysis, data storage, wireless transmission and reception and GPS synchronization. The master unit hardware is made up of 3 components.

1. Processor and storage: A laptop or a PC is used as the processing and storage device. The laptop used has a Windows 2000 operating system. Any updated version of the operating system would serve the function of processing and storage. It has a hard disk which is used for storage of data records. The minimum free space required on the hard disk is 1.65GB if a month's data is to be stored. The laptop has a Intel P3 processor, which meets all the processing requirements. The laptop has serial ports for connecting serial transceiver and GPS receiver.

2. Wireless transceiver: The same model of transceiver (model# DGRO9RFS manufactured by FreeWave Technologies, Inc) is used by the master unit as that used by the slave unit. The transceiver is connected to the comm port of the laptop and data transfer takes place through the serial interface provided by the operating system.

3. GPS receiver: A GPS receiver manufactured by Meinberg, model number GPS161AHS is used to obtain GPS signals from the satellite in order to synchronize the CB monitoring system with the GPS clock. The receiver has an antenna that needs to be mounted so as to have a direct visibility of less than 8˙ above horizon. The terminal unit of the GPS clock is connected to the laptop through a serial interface. The clock signal is received by the laptop and the software uses it to synchronize the system clock.

C. Software

Slave unit software

The slave unit software is implemented in Borland C++. The functions can be classified into two categories

1. Hardware dependent functions: These functions depend on the hardware for achieving the desired goal. The Hardware initialization function, A/D interrupt and memory storage function belong to this category.

2. Hardware independent functions: These functions are independent of the hardware and the code can be reused even if the processor changes as long as it can be compiled on the new processor.

Table XI lists the functions developed, their category and what they do. The A/D interrupt function and the serial communication interrupt functions make the software event driven. Whenever an A/D conversion takes place the ADInterrupt() interrupt function fetches the converted digital values from the ADC and stores them in a cyclic buffer in the processor's main memory. The EventCheck() function checks if a trip or close event has occurred based on the values of the trip and close initiate signals. If an event has occurred the DataRecord() function starts recording the data from cyclic into flash memory. The cyclic buffer also contains data from prior to the moment when the event occurred. This data provides insight about the conditions prior to the events and is also recorded into flash memory with the post event data. The MemTransfer() function is used to transfer data to and from the flash memory. When a record has been stored, the slave asks the master to accept data file and upon acknowledgement sends the data file.

Whenever the system is not recording, the serial port interrupt is enabled and any commands received from Master unit are executed. Fig. 14 shows the flow diagram of the slave system software.

Table XI. Slave software functions

Name	Hardware dependent	Function
HardwareInit()	Yes	Initializes the hardware according to the parameters in config file
ADInterrupt()	Yes	Fetches data from ADC buffer upon completion of conversion
SerInterrupt()	No	Runs interrupt routine when data is received on serial port
CheckEvent()	No	Checks if an event has occurred
RecordData()	Yes	Records data if an event is detected
SendData()	No	Communicates with master unit and sends recorded data through serial port
SendConfig()	No	Communicates with master unit and sends system configuration through serial port
ChangeConfig()	No	Receives configuration from master, stores it in a file and initializes the hardware according to new configuration
RestartSystem()	Yes	Restarts the system on receiving command from master unit
Synchronize()	Yes	Synchronizes the slave system clock to the master system clock

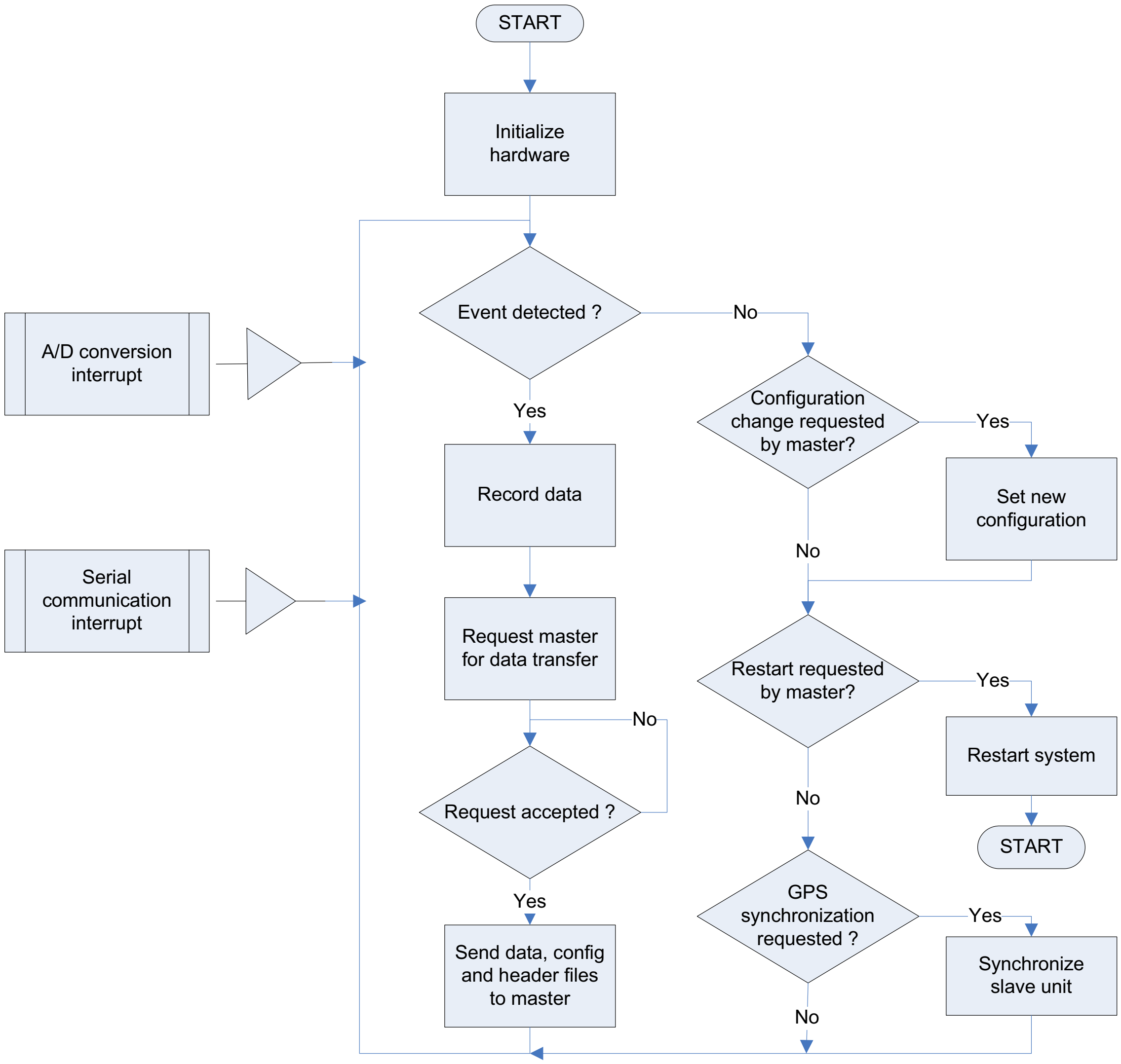


Fig. 14. Flow diagram of slave unit software

Communication protocol

The communication protocol forms the link between the master and slave unit softwares. A class named CommRS232() is designed to implement the communication protocol between the master and slave unit. The class implements methods that facilitate communication over serial port. Its main functions are

- Relay commands from master to slave

- Transfer data and configuration information from slave to master
- Transfer new configuration information from master to slave

The class has methods that implement the communication protocol and provides interfaces which allow other classes or functions to access the communication facilities. This object oriented approach allows ease of development and software maintenance. Thus, even if the slave or master unit software algorithms change the communication protocol class doesn't have to be changed. The next few paragraphs describe the details of the communication protocol. The methods and interfaces provided by the class implementing the protocol are listed in Table XVIII in Appendix A.

The wireless system designed works in a point-to-multipoint mode. In this mode the master sends out the same message to all the slave units and the message is not acknowledged by the slaves. However when slaves send a message to the master the message is acknowledged by the master. The return link is thus the strong one. This protocol is implemented internally by the wireless devices used for communication.The communication protocol used by the wireless transceivers is proprietary and thus varies with the company designing the modems. The communication protocol implemented in the software is designed so as to work with any proprietary protocol as long as the proprietary protocol satisfies data transfer requirements.

The protocol designed for Master-slave communication enables each slave unit to identify if the message is meant for it. Each slave is assigned an ID which is one byte long. The range of IDs is from 0 to 255. The ID 0 is reserved to mean “all slaves” and the ID 1 is reserved for the Master unit. Thus there can be a maximum of 254 slaves per master. The intended message is also similarly coded into a 1 byte code, known as command code. The can be a maximum of 256 command codes. Table XII lists the command codes used for different commands.

Table XII. Master side view of communication codes

Command	Code (Hex)	Sent /Received	Result of execution
CONFIGURATION COMMANDS			
Send config	11	Sent	Master unit requests configuration information from slave
Received config	12	Sent	Master unit confirms receipt and exits config file transfer algorithm
Change config	13	Sent	Master unit commands slave to change configuration
Ready to receive config	14	Received	Master unit starts transfer of config file
Changed config	15	Received	Master unit reports that configuration has been changed and exits config change algorithm
DATA TRANSFER COMMANDS			
Ready to send data	21	Received	Master unit detects that data is available and starts data transfer algorithm
Ready to Accept Data	22	Sent	Data transfer algorithm sends request to slave to start data transfer
Packet acknowledge	23	Sent	Master recipes a data packet and stores it in buffer
Data transfer complete	24	Received	Master exits binary data transfer algorithm
Sending config file	25	Received	Master starts config file reception algorithm
Config file received	26	Sent	Master exits config file reception algorithm
Sending header	27	Received	Master starts header file reception algorithm
Header file received	28	Sent	Master exits header file reception algorithm
GPS SYNCHRONIZATION COMMANDS			
Begin GPS Sync	31	Sent	Master activates GPS synchronization algorithm
T1	32	Received	Master receives time signal and stamps it with current time (T2)
T3	33	Sent	Master transmits time signal to slave with current time stamp (T3) and waits for T1 or sync complete
Sync complete	34	Received	Master exits GPS synchronization algorithm
MISCELLANEOUS COMMANDS			
Restart	51	Sent	Master sends this command to slave to restart slave unit

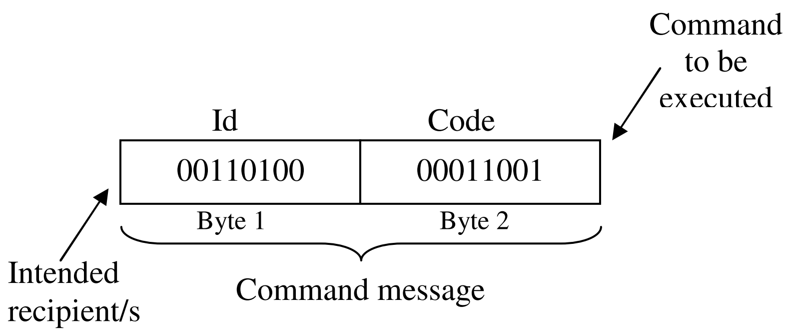


Fig. 15. Command message structure

The ID byte and the command code are combined to form a 2 byte message as shown in Fig. 15. If all slaves are to execute the same command, the ID byte is set to zero. The configuration commands shown in Table XII allow the master unit to communicate with the slave unit in order to perform user specified configuration tasks and some automated configurations tasks. The commands are used to request current configuration from a slave, acknowledge receipt of configuration, send new configuration to a slave and acknowledge change of configuration. The data transfer commands are used to detect that slave is ready to send data, receive data, config and header files from slave and acknowledge the receipt of data. The GPS synchronization commands are used by the GPS synchronization algorithm described later in this chapter. Other commands like restart allow the user to control slave operation.

Data transfer

The command codes are meant only to contain messages for operations that the slave has to perform. A similar but slightly different method is applied for transfer of data between the master and slave units. The data is divided into packets the maximum size of which is chosen based on the wireless transmission bandwidth and can be configured through the user interface. Each packet is made up of two parts. The

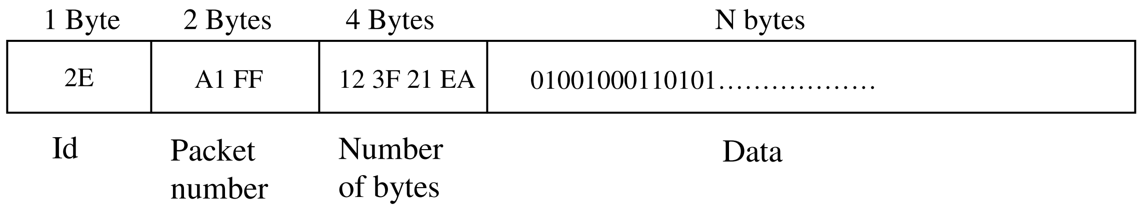


Fig. 16. Data packet structure

first part consists of packet information and the second part consists of data. Fig. 16 shows the structure of the transmitted packet. The data contained in the packet is in binary format but is represented in Hexadecimal base in the figure for convenience. The first byte is the slave id. The next two bytes represent the packet number in unsigned int format. There can be a maximum of 32768 packets before the number again goes to zero. The next four bytes specify the number of bytes 'N' contained in this packet. The information is in unsigned long int format. Thus the maximum number of bytes can be 2^{32}-1. The next N bytes contain the data bytes from the record. The data bytes are 2 byte integers in two's complement format.

When the slave unit completes recording of an event, it requests the master to accept data. The master unit activates the data reception software and sends and acknowledge to the slave unit. The slave unit then starts transfer of data packets. The master unit receives the packet and checks if it contains the specified amount of data. If the packet size is correct, the master unit confirms reception of the package with an acknowledge signal. If the slave does not receive an acknowledge message from master after a certain time period, it repeats the data packet. When all data packets have been sent and acknowledged, the slave unit sends a “Data transfer complete” signal to the master unit and the master unit data transfer algorithm completes and transfers control to the configuration file transfer algorithm. Fig 17 shows the flow diagram of the data transfer algorithms on the slave and master unit.

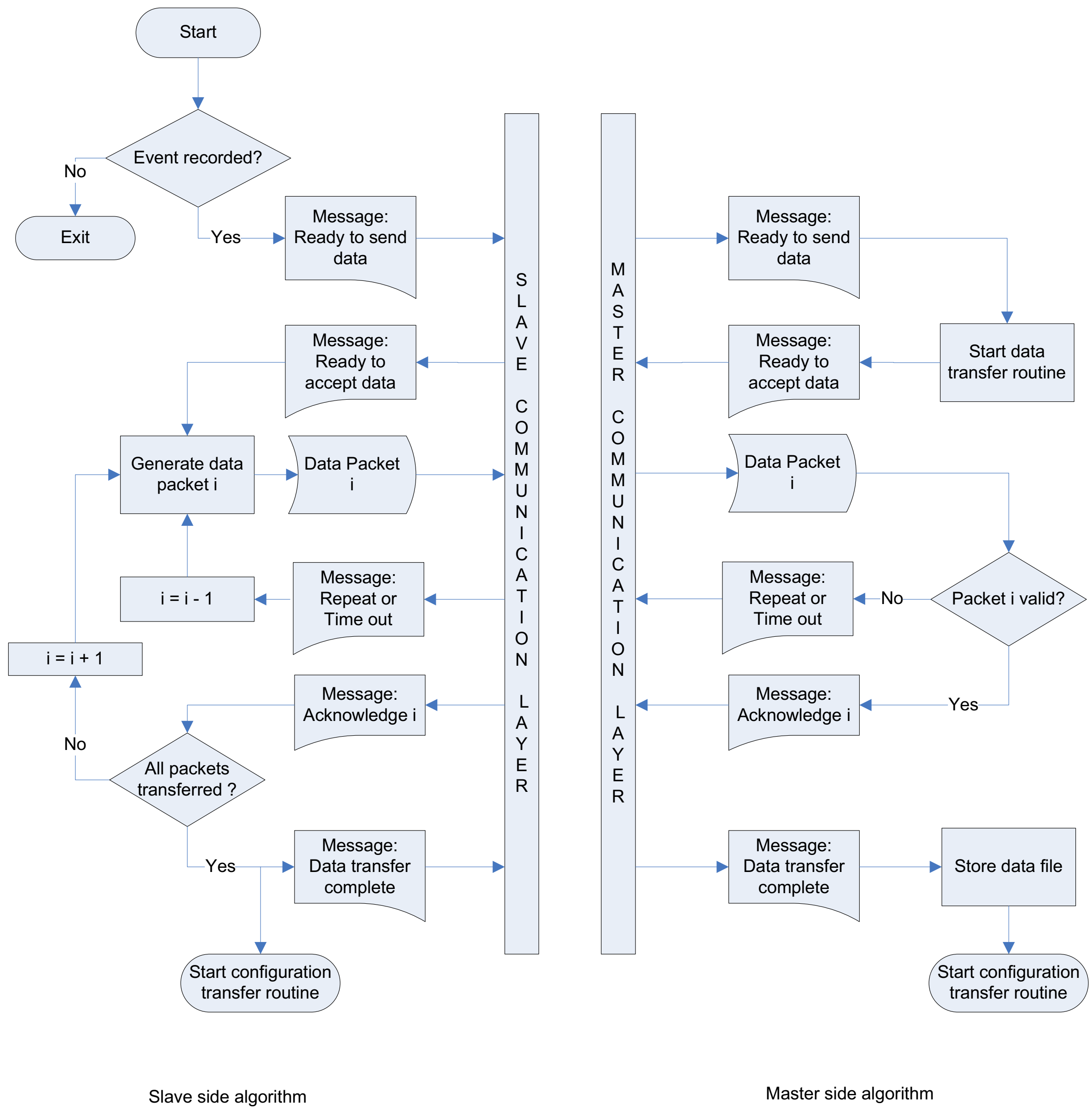


Fig. 17. Data transfer algorithms

Configuration and header file transfer

The configuration and header file transfer algorithms are the same as the data transfer algorithm except that the files are so small that the algorithms do not have to break them into multiple packets. Also the N bytes of the package are in ASCII format for ease of conversion to text format files.

Master unit software

The main functions of the master unit software are

1. Communication with the slaves
2. Graphical user interface for control
3. GPS synchronization
4. Data analysis and storage

The master unit software is an event driven software and also uses a graphical user interface to allow the user to control the monitoring system. It is developed in Visual C# which allows for easy development of both these features.

Graphical user interface

The graphical user interface enables the user to control the monitoring system through different form interfaces like buttons, textboxes etc. displayed on the windows GUI. Detailed description of GUI usage is given in Appendix A. Table XIII lists the different GUI form interfaces developed and their functions. Table XIV shows the parameters that can be configured for signals. The slave unit parameters that can be changed remotely through the device configuration form (Fig. on p.86 in Appendix A) are listed in Table XV. The interface also allows the user to enter the signal details and the software scaling factors which are used to identify the signals in COMTRADE configuration files.

Table XIII. Windows forms designed in master unit software

Form name	Function
Main window	Displays the slave units present in the local system, provides user with a context menu to perform different operations like configuration, synchronization etc. on a device or group of devices
Configuration form	Displays the configuration of selected slave unit and allows the user to modify it
Signal information form	Displays the channel number, signal name and type for all signals acquired by the slave unit and allows the user to change them
Add device form	Allows the user to set configuration for a new device, uses the same template as the configuration form
Record log window	Displays the logs of the events recorded (Time, Data and Event type) on the selected breakers. Allows the user to select a particular log entry and view the details of the record
Waveform display window	Displays the details of the selected record. It displays the channel number, name, record time and the recorded waveform graphically.

Table XIV. Configurable signal parameters

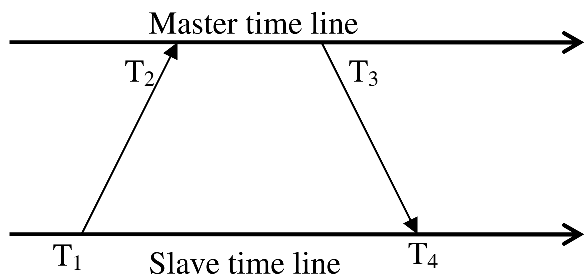
Parameter	Significance	Range of values
Channel number	The hardware channel number on which the signal will be recorded	Numeric (<max channels)
Signal name	Name of the recorded signal	Alphanumeric
Signal type	Type of signal	High voltage/ Low voltage
Trigger	Whether this signal triggers recording or not	Yes/No
Threshold	The value of signal above which recording is triggered	Unsigned float $<$ 130

Table XV. Remotely configurable slave unit parameters

Parameter	Significance	Range of values
Device Id	Used to identify the slave device and to communicate with particular slave unit	Numeric (non-repeatable)
Device Name	Name of slave device for filing	Alphanumeric(25 char max, no white spaces)
Breaker	Number or name of breaker on which device is set up	Alphanumeric(25 char max)
Location	Location of device (substation name, area name)	Alphanumeric
Analog channels	Number of analog recording channels used in slave unit	Numeric
Digital channels	Number of digital recording channels used in slave unit	Numeric
Line frequency	Frequency of power line	50 or 60Hz
Sampling rate	Sampling rate used by ADC of slave unit	positive float(Hz)
Record duration	The duration for which slave unit must record signals when an event occurs	Numeric(seconds)
Data type	The format in which data is stored in the slave unit memory and master unit storage device	Binary or ASCII

GPS synchronization

The algorithm used to synchronize the slave unit to master unit is similar to the Simple Network Time Protocol (SNTP) [25]. The algorithm implemented does not work on the TCP or UDP protocol but uses the logic of the SNTP algorithm. Fig. 18 shows a simple representation of one cycle of the algorithm.



$$\theta = \tfrac{1}{2}\{(T_2 - T_1) + (T_3 - T_4)\}$$

Fig. 18. Representation of GPS algorithm

The steps in the GPS synchronization algorithm are as follows

1. Upon synchronization request by master, stamps current local time (T1) on a time request packet and sends to master.

2. Upon receipt of this packet, master unit stamps reception master-time (T2) and returns it to slave immediately upon stamping current time (T3).

3. Upon receipt the slave processor computes round-trip delay d and local clock offset t as

   d = (T4 - T1) - (T3 - T2)

   t = ((T2 - T1) + (T3 - T4)) / 2

   where T4 is the local receipt time. Table XVI summarizes the timestamps used in the algorithm.

4. The clock time is updated to be current time + t.

5. To get a good estimate the steps above are repeated 5 times or till t is less than 100μs.

Table XVI. GPS synchronization timestamps

Timestamp Name	ID	When Generated
Originate Timestamp	T1	Time request sent by slave
Receive Timestamp	T2	Time request received by master
Transmit Timestamp	T3	Time reply sent by master
Destination Timestamp	T4	Time reply received by slave

Data analysis and storage

The master unit receives data from all slave units in the system. The data storage algorithm stores the data on the hard drive in COMTRADE format files. COMTRADE format specifies 3 files for each data record [24].

1. Header file: The header file is an optional ASCII text file created by the originator of the COMTRADE data. The information contained in the header file may however be very useful for applications that use the recorded data to analyze the state of circuit breaker. The header file format is ASCII. It contains information about the location of breaker, the trigger for recording, record length, fault duration, comment and data format. The comment field can be used to pass information to the applications about the type of breaker. Fig. 19 shows one of the header files recorded by the designed prototype. The header file has an extension .HDR.

2. Config file: The configuration file is an ASCII text file that provides the information necessary for a human or a computer program to read and interpret the data values in the associated data files. The configuration file is in a predefined, standardized format so that a computer program does not have to be customized for each configuration file. The configuration file contains the

```
Location       :   Breaker F290 at Obrien
Machine name   :   CB01
Record Number  :   001
Trigger        :   Status on channel 1 'Trip Event'
Trip time      :   23:20:28.632  Sun 26 Jun 2005 (176)
Events occurred:   001
Record length  :   180.0 cycles
Fault duration :   15 ms
Comment        :   THW-,20B0,WH,R3,1234567,(NONE)
Data format    :   binary
```

Fig. 19. Header file generated by CBMS

following information.

(a) Station name, identification of the recording device, and COMTRADE Standard revision year;

(b) Number and type of channels;

(c) Channel names, units, and conversion factors;

(d) Line frequency;

(e) Sample rate(s) and number of samples at each rate;

(f) Date and time of first data point;

(g) Date and time of trigger point;

(h) Data file type; and

(i) Time Stamp Multiplication Factor.

Configuration files have .CFG extension. A sample config file is displayed in Fig. on p.67 in Chapter VI.

3. Data file: The data file contains the data values that are scaled representations of the sampled event. The data must conform exactly to the format defined in the configuration file so that the data can be read by a computer program. The

data file type (ft) field defined in the configuration file specifies the file type. For binary data files ft is set to binary. For ASCII data files ft is set to ASCII. The data file contains the sample number, time stamp, and data values of each channel for each sample in the file. All data in data files are in integer format. The circuit breaker monitoring system uses the binary format for data files as it occupies almost one-third as much space as an ASCII file. The data files have a .DAT extension.

To identify the records, the files are named using the IEEE file naming convention [26]. The graphical user interface allows the user to view a log of the records stored on the system. By selecting a particular log the user can view the signal waveforms.

Whenever an event is recorded the data analysis algorithm detects if its a trip or a close event and notifies the user of the occurrence of the event. A dynamic link library (dll) file is designed which holds variables that specify if an event has happened and the type of event. This file can be used by applications that want to be notified whenever an event occurs.

D. Conclusion

This chapter described the implementation of a prototype Circuit Breaker Monitoring System. The hardware required and its integration details were described for both the slave and the master unit. The software developed to perform the data acquisition function on the slave unit was discussed. The development of the software for master unit, which co-ordinates the data acquisition among slaves and makes the data accessible to other applications was discussed. The next chapter describes the evaluation of this prototype design.

CHAPTER VI

SYSTEM EVALUATION

A. Introduction

Any system developed must be evaluated for the desired performance. The two main testing procedures followed in the testing of circuit breaker monitoring system are

- Laboratory testing or Controlled testing
- Field testing

Laboratory testing is done in a controlled environment in modular fashion i.e. all modules are tested for their functionality. Field testing is done in field environment with all factors present that can affect the performance of the system. Laboratory testing is more thorough while field testing is more strenuous. This chapter describes in detail the procedures used to evaluate the system in laboratory and field environments.

B. Laboratory testing

Laboratory testing involves individual module testing and integrated system testing.

Individual module testing

The functionality of each module of the CBM system is tested after its design. The signal conditioning boards were tested for both high-voltage and low-voltage signals. Any DC offset in the output waveforms was removed and the gains were calibrated to scale the output signals in the ± 5 volt range. The A/D conversion module was tested with different types of signals - sinusoids, square waves, DC and scaled trip reference signals. The accuracy of conversion was tested and the appropriate scaling factor was determined. The processor module and the associated software was tested by repeatedly triggering the recordings using artificial trip signals. The performance was monitored and it was observed that recordings were made accurately for all triggers that were applied. The wireless system was tested in lab environment with 300 meters distance between the two units. The test message transmissions were sent and received accurately.

The processor system on the master side was tested in co-ordination with the slave side processor. Artificial triggers were applied to the slave unit and the master was turned on to receive records. It was observed that records were stored on the master side for each trigger applied to the slave system.

Integrated system testing

The circuit breaker monitoring system was evaluated in the laboratory using signals recorded previously in the field. The AVO test set equipment was used to replay the waveforms using Relay Assistant software [27]. The test setup at Texas A&M university laboratory can play back only three high voltage channels so the testing is done 3 channels at a time. Fig. 20 shows the waveforms replayed by the test equipment to the CB monitoring system. It can be seen that the waveforms are part of a reference trip record. The working of the slave unit software is observed on the monitor connected to the slave unit. This information is used for debugging the data acquisition software. The signals are captured and transmitted to the master unit. The data collected on the master unit is then plotted and the waveforms are compared to those at the input. Fig. 21 shows the waveforms of the recorded signals. It can be seen that the time scale of the signals input to CBM and the signals recorded by CBM is different. This is because duration of recorded signals is 1 sec and includes about 200ms of pre-event data.

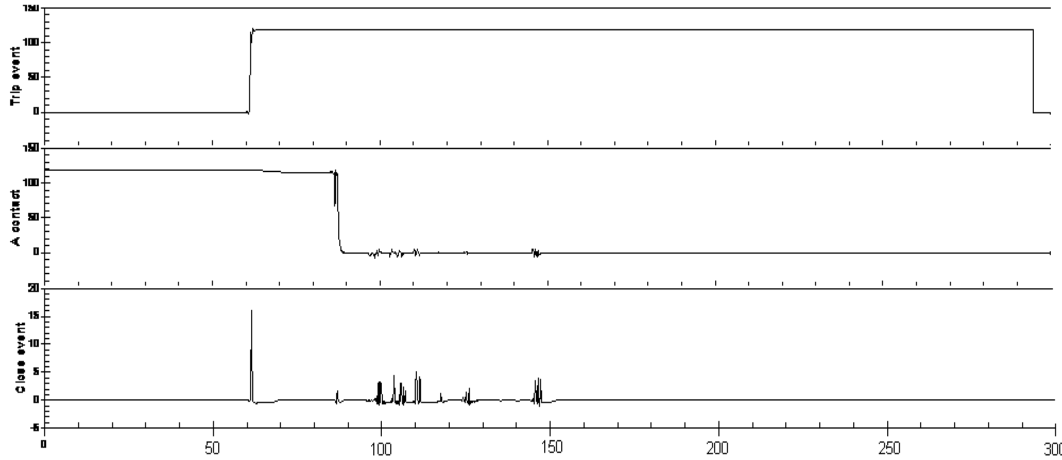


Fig. 20. Trip event, a contact and close event reference signals

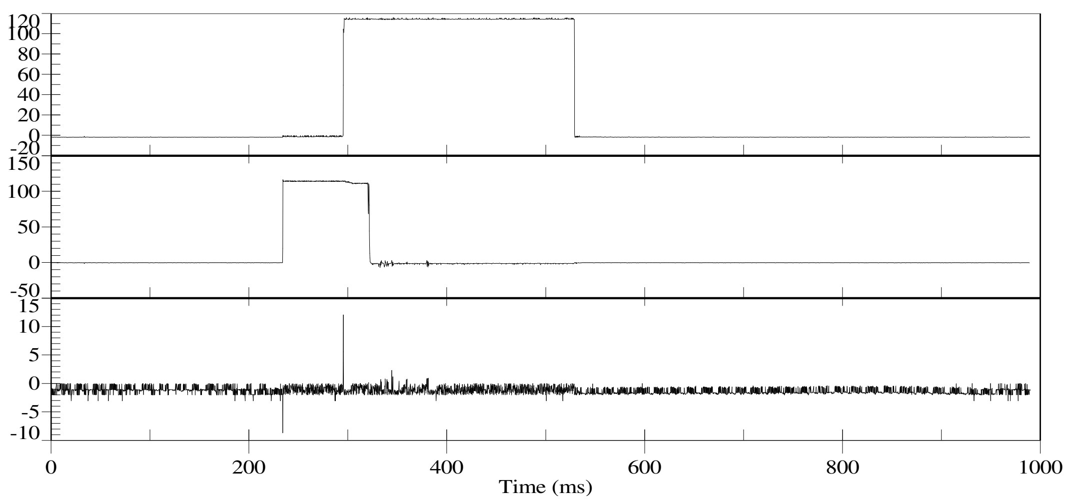


Fig. 21. Trip event, a contact and close event signals recorded by CBM unit

Comparison of the two figures indicates that some noise is introduced during recording. This is due the combined effect of the test equipment and the power converters used for powering the signal conditioning unit.

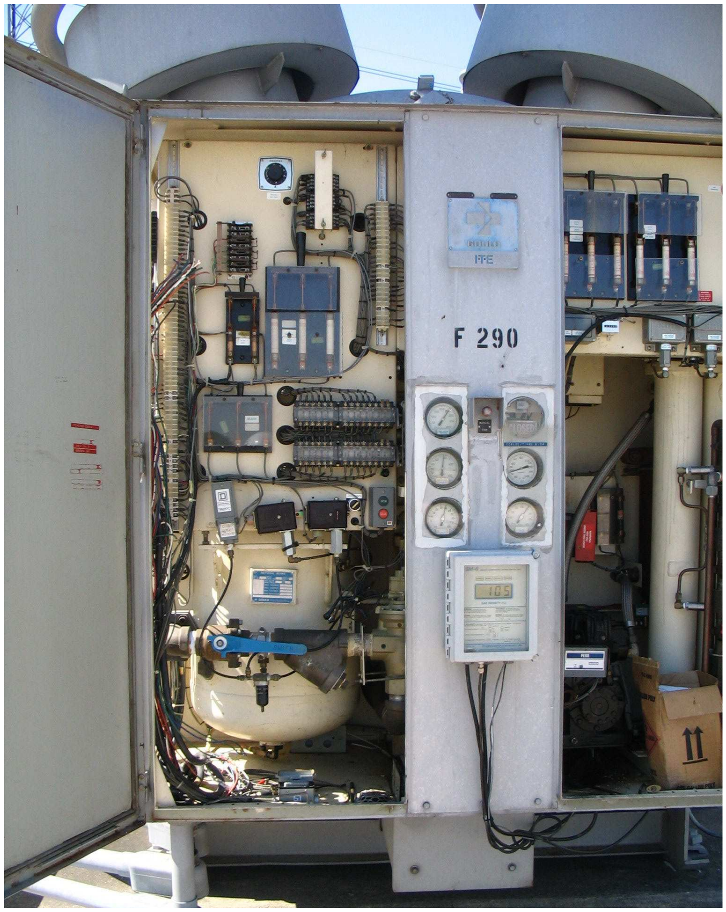


Fig. 22. Breaker wiring panel

C. Field testing

The circuit breaker monitor was tested in a field setup at one of the local utility company's substations. The slave unit was set up at a breaker which operates on a 345kV line. The slave unit hardware was made weather-proof by sealing the metallic box with a sealant. The temperatures at the test site can go as high as 150$^{\cdot}$F. The electronic components used in the design were chosen so as to meet the required temperature specifications. Fig. 22 shows the breaker panel from which signal wires were drawn. Fig. 23 shows the slave unit installed at the breaker.Installation was non-invasive, the time required was less than one hour and required only two personnel.

Fig. 23. The slave unit set up near the breaker

The unit was energized by AC power drawn from the breaker AC line.

The breaker is located at an approximate distance of 150m from the control house. The master unit wireless transceiver was packed in a weather proof box and installed outside the control house so as to have a line of site between the two transceivers. The master unit transceiver is connected to the laptop through a RS232 cable onto the serial port. The master side software is installed on the laptop and initialized to start reception.

Fig. 24 shows the waveforms of the Close initiate, B contact and A contact signals recorded by the monitoring system during a close event. Fig. 25 shows how the phase currents change on a close event. The figure has the same time scale as Fig. 24. By comparing the ideal signal waveforms shown in Fig. 3(b) to those shown in Fig. 24 it can be concluded that the Circuit Breaker Monitoring System records the signals effectively.

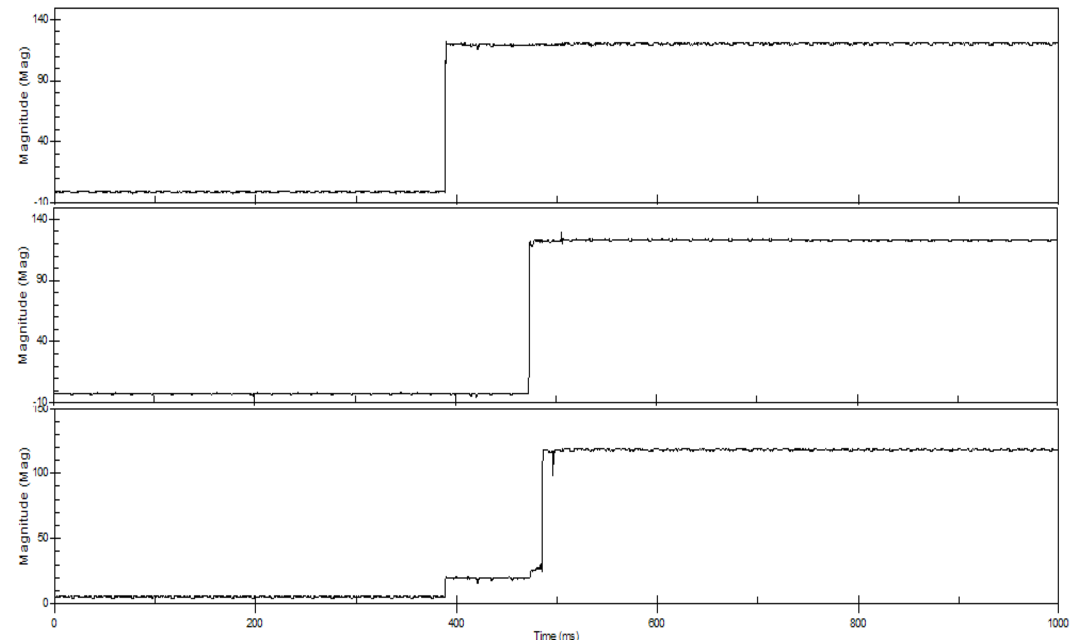


Fig. 24. Close event record

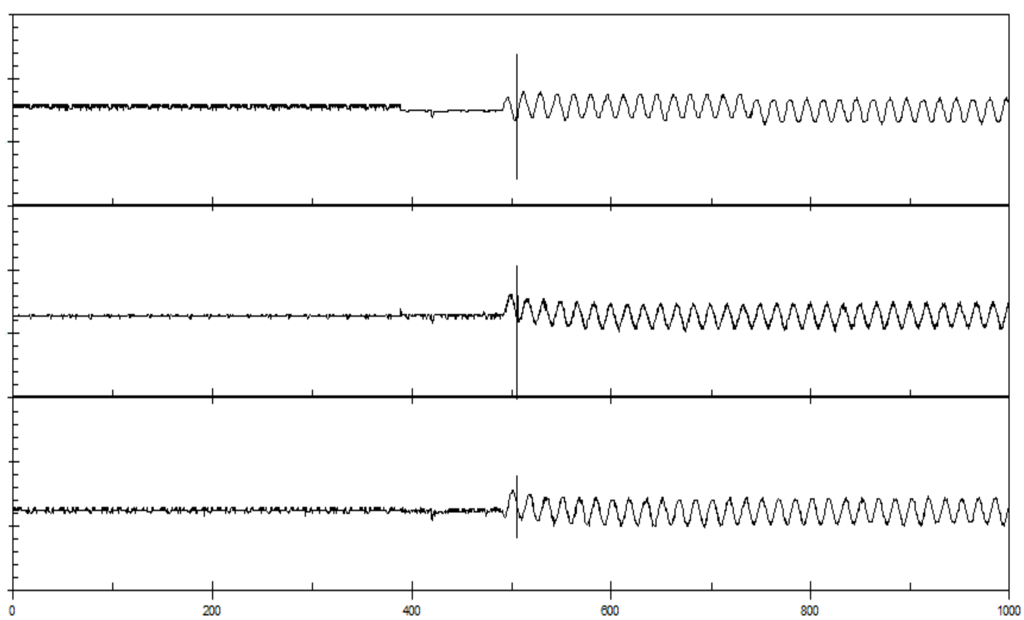


Fig. 25. Phase currents measured during close event

Table XVII. Field evaluation of monitoring system

Parameter	Significance	Observed value
Transmission range	Distance between master and slave transceivers. Communication must function even at this distance	300m
Transmission time	Time required to transmit 1 second of captured data at 5700kHz	6 min
Installation time	Time required to install the CBM on a breaker	<1 hr
Installation cost	Cost of field installation	Labor cost + minimal wiring (<$15)

```
CBM1 at Obrien,1999
15,15A,0D
1,Trip Event,,,V,0.003967,0.0,0,-32768,32767
2,Bkr close - A,,,V,0.003967,0.0,0,-32768,32767
3,Bkr open - B,,,V,0.003967,0.0,0,-32768,32767
4,X coil,,,V,0.003967,0.0,0,-32768,32767
5,Spare 1,,,V,0.000031,0.0,0,-32768,32767
6,Spare 2,,,V,0.000031,0.0,0,-32768,32767
7,Close Current,,,V,0.000031,0.0,0,-32768,32767
8,A phase current,,,V,0.000031,0.0,0,-32768,32767
9,Close Event,,,V,0.003967,0.0,0,-32768,32767
10,Supply DC,,,V,0.003967,0.0,0,-32768,32767
11,Y coil,,,V,0.003967,0.0,0,-32768,32767
12,Spare 3,,,V,0.000031,0.0,0,-32768,32767
13,Trip Current 1,,,V,0.000031,0.0,0,-32768,32767
14,B phase current,,,V,0.000031,0.0,0,-32768,32767
15,C phase current,,,V,0.000031,0.0,0,-32768,32767
60
1
5760.37,5760
28/06/2005,11:58:42.816310
28/06/2005,11:58:43.166064
BINARY
1.0000
```

Fig. 26. COMTRADE file for trip recording

Table XVII shows the parameters used for evaluation of the field system and their observed values. The COMTRADE config file for the recorded trip signals is listed in Fig.26.

D. Conclusion

This chapter discusses the evaluation of a prototype of the circuit breaker monitoring system in laboratory and field conditions. System testing in laboratory by replaying previously recorded signals is described. Field testing performed in a substation is described and the recorded results are compared.

CHAPTER VII

APPLICATIONS

A. Introduction

The chapters so far have described the design, implementation and evaluation of the circuit breaker monitoring system. This chapter describes the applications that can be interfaced with the developed monitoring system. These applications will use the data recorded by the circuit breaker monitoring system and use it to preform different types of analysis activities. According to the IEEE Guide for the Selection of Monitoring for Circuit Breakers [28] monitored data can be used to

- Determine the condition of a specific circuit breaker
- Determine the condition of the circuit breaker support and control functions and facilities
- Optimize maintenance activity
- Develop an understanding of the condition of a larger population of circuit breakers in similar circumstances by examining a representative sample of the population
- Improve circuit breaker utilization
- Reduce circuit breaker failure rates
- Add to the circuit breaker body of knowledge available to determine the cause of failures after the fact
- Improve economics of equipment operation

The data recorded by Circuit Breaker Monitoring System can be used in software applications which make the uses described above a cost-effective means of increasing system reliability. This chapter describes the applications that can be developed to make effective use of local and system-wide data and the potential benefits they would have.

B. Use of local data

Local data is defined as the data collected and processed at a substation level. The data is sent to the control house where it is processed and stored. If an application makes use of only data from this particular substation to derive information about the breakers in the substation, then it is said to be a local data oriented application. Such an application has low processing and storage requirements and is readily implementable in a distributed environment. Some of the local applications that can be designed to work with CBM recorded data are described below.

Local data applications

Automated circuit breaker analysis

The circuit breaker monitoring system can allow personnel to do away with the current maintenance system in which personnel go to the breaker physically and record signals using portable recorders. This will save the utility a lot of personnel hours. An automated monitoring and analysis system developed by a group of researchers at Texas A&M University was used as a test application [6]. The automation software consists of a signal processing module and an expert system module. The two modules process the voltage and current signals recorded by the circuit breaker monitoring system, diagnose and report any abnormalities that are discovered. The analysis

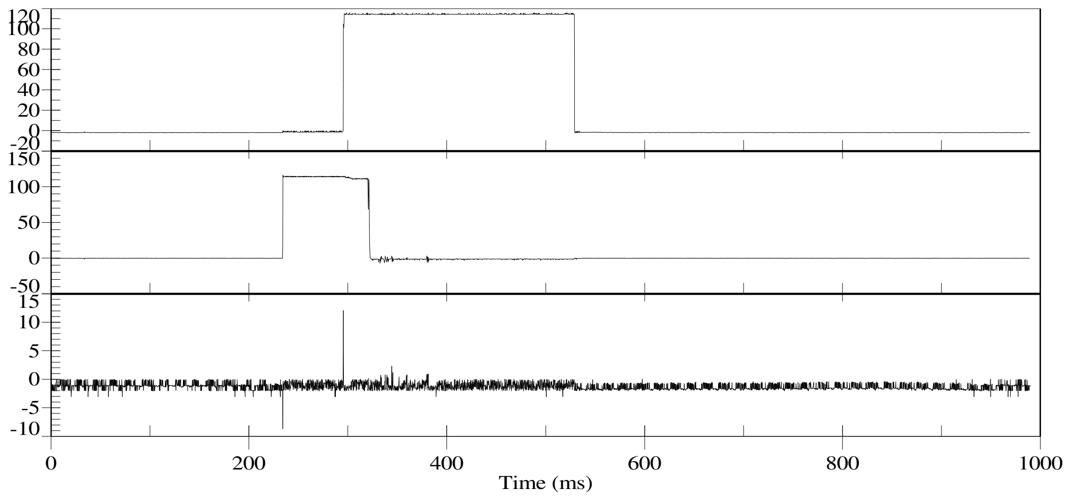


Fig. 27. Trip event, a contact and close event signals recorded by CBM unit

software was interfaced with the monitoring system through a file repository that uses COMTRADE format files for data storage. Pre-recorded waveforms were played back to the monitoring system. The monitoring system triggered the analysis software upon receiving the recorded data and it performed the analysis and reported the results. The results reported by the analysis application, for the waveforms shown in Fig. 27 (same as Fig. 21 replicated here for convenience), are shown in Figure 28.

Automated warning alarm system

This application is designed as a supplement to the primary alarm system thus increasing its reliability. The application uses standard algorithms or expert systems to identify events on the breaker. Depending on how critical the event is, it generates different alarms that alert the maintenance system and the operators. This alarm system is specially effective when certain abnormalities are observed in the circuit breaker control circuit signals but the breaker continues to work normally. In such cases the unnoticed abnormalities may become cause for failure. If the application can identify signal abnormalities by regularly monitoring these signals and generate maintenance alarms on detecting them, then equipment failure rates and downtime can be considerably reduced.

```
050623,155835542,-5D,SRB1,P930,HLP,GE,FK-69-7500,10077937,O
REPORT ON EXPERT SYSTEM CB RECORDS AUTOMATED ANALYSIS
Copyright: Texas A&M University, 2001, 2002
Customized for: CenterPoint Energy
***********************************************************************
DFR record file name: 050623,155835542,-5D,SRB1,P930,HLP,GE,FK-69-7500,
10077937,Open.dat
Creation date: 23 Jun 2005
Creation time: 15:58:35.542
Station ID: SRB1
Device ID: P930
Company name: HLP
Brkr manufacturer: GE
Brkr type: FK-69-7500
SAP ID: 10077937
Comment: T
-------------Expert System Log--------------
The record indicates an opening operation!
R11: Yard voltage unstable!
Excessive dip unrelated to close/trip coil activity!
R17: 'A' contact bouncing!
R18: 'A' contact premature!
R24: 'B' contact premature!
R27: Trip coil current flat!
R42: Phase A Current did not drop!
R45: Phase B Current did not drop!
R48: Phase C Current did not drop!
R68: Velocity decreased!
R72_a: Sequence A-B violated!
------Maintenance & Repair Information------
Check substation battery, charging system, and control cables.
Check auxiliary assembly, contacts, and linkage.
Check trip circuit and harness connections.
Check Phase currents connections. There may be a bad interrupter.
This breaker is slow. The auxiliary alignment needs to be checked.
```

Fig. 28. Analysis report from CBMA application

Predictive maintenance alarm system

The predictive maintenance alarm system application is an enhanced version of the warning system. The warning system is an online application which raises alarms only when abnormalities occur. However, sometimes it may be too late to act on the abnormality alarm before the breakdown occurs. The predictive maintenance application would combine the information extracted from recorded data with maintenance history of the breaker to provide better information about the state of the breaker and remaining life time of breaker. This would enable utilities to perform just-in-time maintenance. The recorded data can be processed by this application to extract the following information.

- Precise breaker operation history
- Time delays observed in operation
- Signal parameters that indicate the “well-being” of different breaker components

The application would take the following information from maintenance personnel through a graphical user interface, accessible securely over the internet or intranet.

- Date and time of maintenance
- Type of maintenance
- Details of parts replaced or repaired
- Personnel time spent on maintenance
- Cost of maintenance

The application would have a database of parts containing information about the effective lifetime of parts and the effect of part replacement on the lifetime of breaker.

Using an expert system and probabilistic reliability models, various deductions could be made by combining the maintenance information with breaker operation information. Some of the possible inferences that can be generated are

- The remaining life-time of breaker
- Time interval before next maintenance
- Overall cost associated with breaker over its life-time

The inferences derived by this software can enable utilities to increase the life of power apparatus and make better decisions about equipment maintenance and purchase. Also, whenever abnormalities are detected by the software, just-in-time maintenance can be performed by personnel. This will enable them to reduce costs while improving reliability of service.

C. Use of system-wide data

If the recorded data from all substations in a power system is combined together to make some deductions, then the application is known as a system wide application. System-wide applications can help increase reliability of operation and reduce costs.

Increasing reliability

In a typical power system a lot of data is recorded and monitored. The recorded data is critical for the day to day operation of the system. It is essential that this data be reliable. The circuit breaker data can provide information about the status of a circuit breaker, whether it is open or close. This data if collected all over the power system can provide information about the topology of the power system. The topology information is also obtained by other means which are more direct like SCADA.

However, the redundant topology information from circuit breakers can be used to verify the consistency of directly measured topology information thereby increasing robustness of data and reducing operation errors. Some applications that can use CBM data recorded at the substation level to improve power system operation and control are described in [29],[30] and [31].

Reducing costs

The predictive maintenance alarm system described in the previous section when implemented over the entire power system can help reduce costs in numerous ways. If the number of maintenances to be performed during one month period over the complete power system or a particular region of the system is known before hand, the maintenance staff can be hired accordingly by the power company. This will enable the utility to maintain the breakers as needed with minimal staff. Reliable operation of well-maintained breakers will help a utility have continuity of service or minimal interruption even during faults by re-routing power, thus reducing costs incurred due to loss of service.

D. Conclusions

This chapter described the different applications that can be interfaced to the circuit breaker monitoring system. The results from integration of Circuit Breaker Monitoring and Analysis application with the monitoring system were discussed. New applications that can utilize the data recorded by CBMS were described. The difference between local and system wide applications was discussed and some possible applications were listed. The applications described can help reduce the costs of operation and maintenance for utilities and also help prolong the life of power equipment.

CHAPTER VIII

CONCLUSION

A. Summary of work

Circuit breakers form a critical component of the power system and require regular inspection and maintenance to ensure reliability of operation. The current maintenance method used involves personnel going physically to the breaker. They record the control circuit signals by operating the breaker and make a diagnosis based on the comparison between recorded signals and reference signals. Some companies have started using automated monitoring of circuit breakers but it is yet to receive wide acceptance. Researchers have come up with methods to analyze the recorded signals and draw conclusions about breaker status. However high cost of implementation compared to the functionality that the automated systems provide is a deterrent to their large scale use. Low cost monitoring and automated analysis systems that cater specifically to circuit breaker monitoring are not available in the market.

A low-cost monitoring system designed specifically to work with circuit breaker control signals was implemented and evaluated. The system can monitor up to 15 circuit breaker signals. A master-slave architecture was defined for the system which reduces implementation cost per breaker by using a single processor to perform functions common to all data acquisition units. The slave unit acquires the signals from the circuit breaker control circuit and converts them to digital form. The signals are then transmitted wirelessly to master unit. The choice to transmit data wirelessly was made to reduce installation costs and increase ease of installation.

The master unit receives the data and stores it in digital form. The data is processed and stored in COMTRADE format files which can be used by a multitude of applications. The master unit has a graphical user interface which allows the user to configure and control the functioning of the system. The master unit also allows the user to view recorded data graphically.

The system was designed so that the recorded data may be combined with other data from the power system. For this reason the monitoring system is synchronized to GPS time and all recordings are accurately time-stamped. The system uses only one GPS signal received at the master to keep the GPS receiver costs to a minimum. The signal is propagated to the slaves through the wireless system and the entire system is synchronized.

A prototype of the monitoring system was evaluated in the field at a substation in Houston belonging to a local utility company. The results obtained were very promising. A fully integrated solution has been designed and a prototype is under development.

B. Contribution

Any new technology is evaluated on the basis of the advancement it has achieved in existing technology and reduction in overall cost. The main benefits of the circuit breaker monitoring system designed are

- Automatic monitoring: The system provides an automated monitoring and event logging solution. This eliminates the need for personnel to go physically to the breaker for inspection.

- Low-cost: The system provides a low cost solution for continuous monitoring of circuit breakers. With the per breaker cost less than $500 the monitoring system can be implemented on large scale, thereby automating the inspection processing and reducing costs further.

- Ease of installation: The system is easy to install and requires only a few minutes of set up time per breaker.

- Ease of use: The system provides a graphical user interface to view recorded data and event logs. The system can be configured and controlled from the master unit set up in the control house. If a virtual network connection is present the system can even be controlled remotely over the internet.

- Standard interface: The system provides data in COMTRADE format file for use by any analysis application. It provides an interface that can trigger analysis applications when an event occurs.

It is also expected that this research and development effort has contributed the following to the area of power systems engineering:

- The requirements and functional specifications for design of a monitoring system

- The architecture of master-slave type monitoring system

- Description of implementation and evaluation of an automatic circuit breaker monitoring system

- Ideas for developing applications that will utilize the recorded data

C. Future work

Future work involving automation of circuit breaker monitoring may include the following:

- Development of a real time monitoring system which transmits recorded information at high data rates. If the data is available for viewing within milliseconds the information can be used by operators to make better decisions while performing control operations on the breaker.

- Integration of data collected by circuit breaker monitors installed all over the power system and making it accessible centrally for system-wide applications.

- Design and development of local and system-wide applications which combine circuit breaker data with other power system data to draw inferences about maintenance and system operation and increase the robustness of data, thereby increasing the overall system reliability.

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APPENDIX A

SOFTWARE DESIGN DESCRIPTION

Communication protocol implementation

The communication protocol is implemented in the master unit software by the class CommRS232. Table XVIII shows the names and functions of the methods implemented by this class.

Table XVIII. Methods implemented by the communication class

Method Name	Parameter List	Function
SendMesg	char SlaveId, string command	Takes the slave id and command string and transmits the 2 byte command message to the slave unit
OnSerialPortEvent	Object sender, SerialDataReceivedEventArgs e	Overrides the default data received method of the serial port object and parses the incoming messages and activates the appropriate routines
ParseMesg	string Message	Takes the message string as input and outputs the byte code for the message
OnDataTransfer	void	Handles the transfer of data packets from the slave unit
SaveData	byte[ ] data	Saves the data packets received into a file on storage device
SendConfig	string configdata	Creates the configuration data packet and transmits it
OnReceiveConfig	Object sender, SerialDataReceivedEventArgs e	Receives the config and header files transmitted by slave

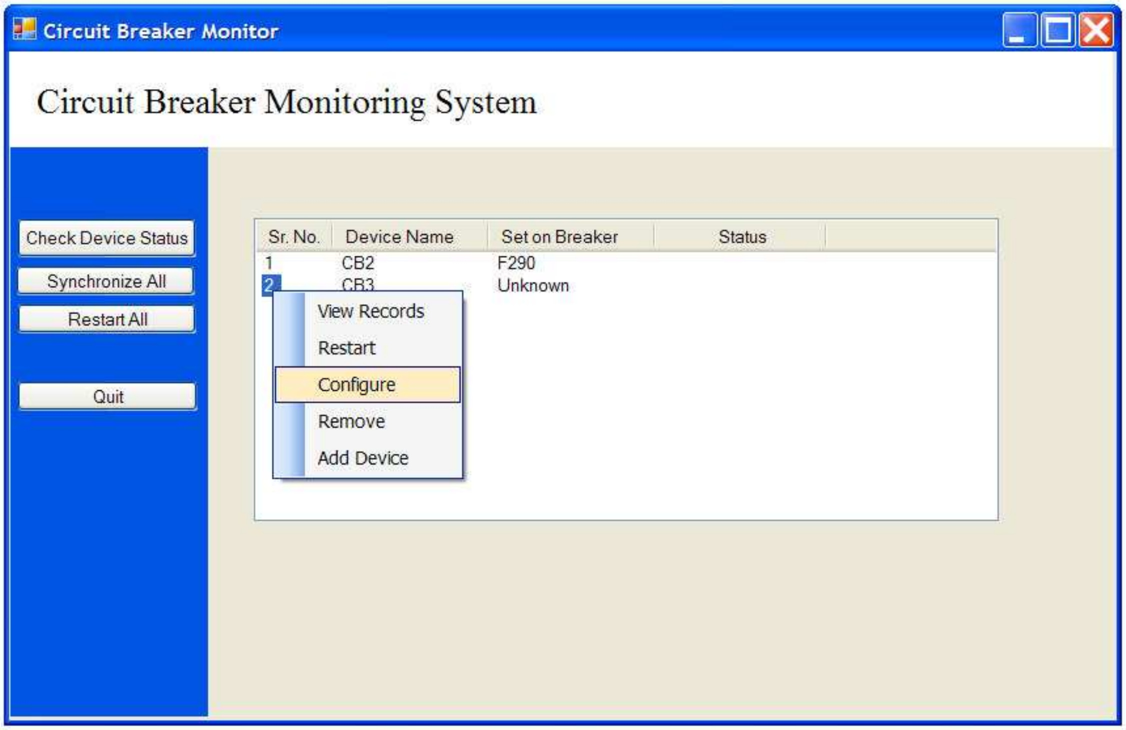


Fig. 29. Main application form showing slave units present in the system

Graphical user interface description

The master unit software provides a graphical user interface for the user to control and configure the system. This section provides the details about the different interfaces and how to use them. Fig. 29 shows the Main window of the master unit software. This windows lists the slave units present in the system. The user can access a context menu shown in the figure by selecting one of the slave units and then using the right click button of the pointing device. The context menu allows the user to view records from the particular slave unit, restart the slave unit, configure the unit and remove the unit. It also allows the user to add a new unit to the system and enter its configuration. Any of these options can be chosen by using the left click button of the pointing device when the option is highlighted. The buttons like Check

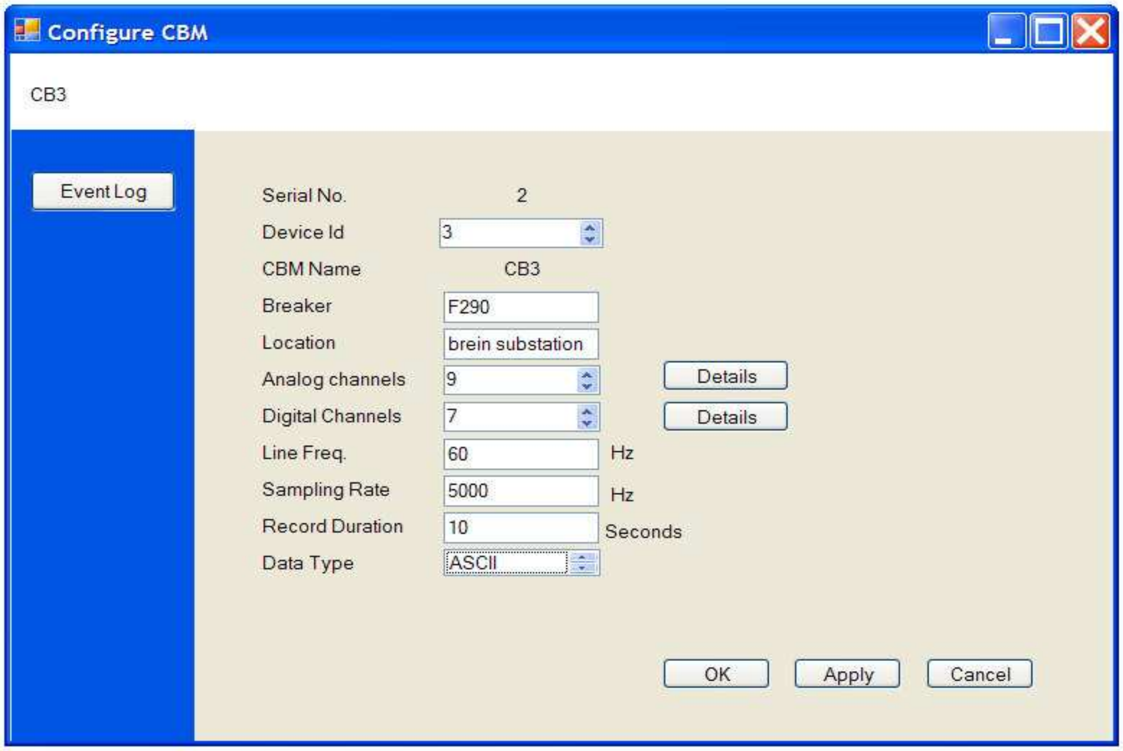
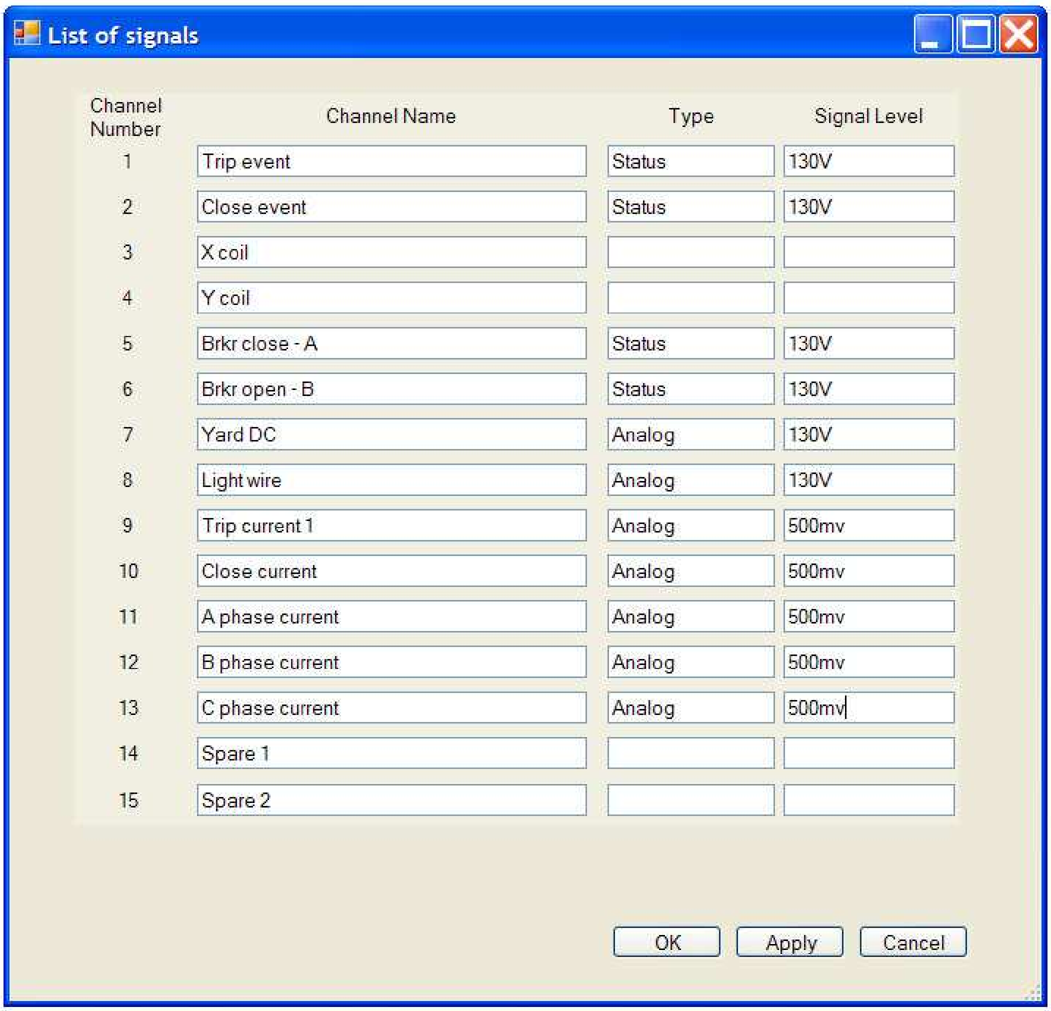


Fig. 30. Form for changing configuration of CBM slave device

device status, Synchronize all and Restart all button perform the respective actions on all slave units. The Quit button quits the master unit software application.

Fig. 30 shows the configuration form designed to allow the user to change the configuration of a slave device. The Event Log button when pressed generates a new form on the screen which displays the list of records belonging to the particular slave unit which is being configured. The details buttons for the Analog and Digital channels display the signal details as shown in Fig. 31. A particular record saved by the master unit can be viewed by selecting it from the event log list. Fig. 32 shows the window that displays the waveforms of the recorded signals.



List of signals

Channel Number	Channel Name	Type	Signal Level
1	Trip event	Status	130V
2	Close event	Status	130V
3	X coil		
4	Y coil		
5	Brkr close - A	Status	130V
6	Brkr open - B	Status	130V
7	Yard DC	Analog	130V
8	Light wire	Analog	130V
9	Trip current 1	Analog	500mv
10	Close current	Analog	500mv
11	A phase current	Analog	500mv
12	B phase current	Analog	500mv
13	C phase current	Analog	500mv
14	Spare 1		
15	Spare 2		

OK Apply Cancel

Fig. 31. Form for changing signal names and type

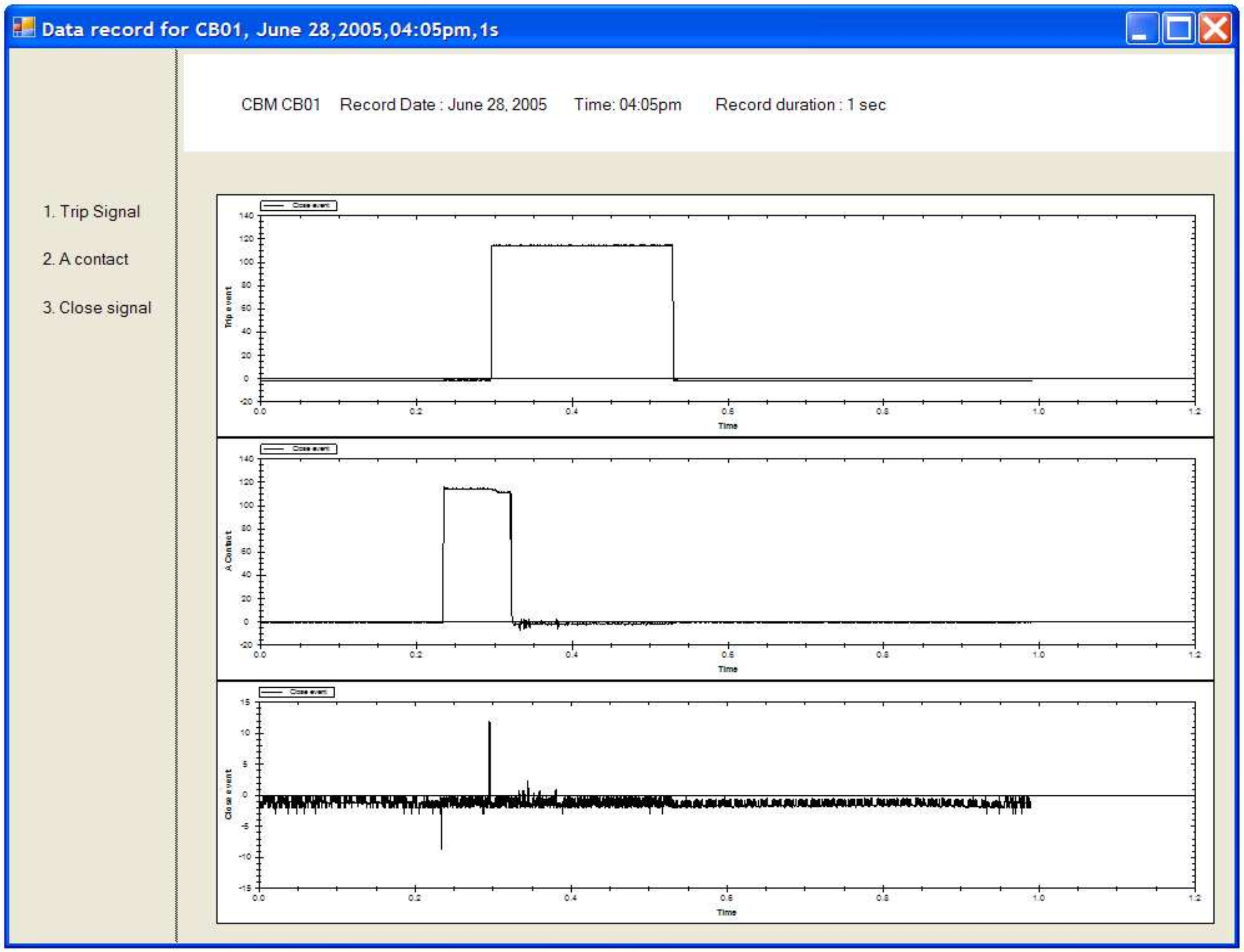


Fig. 32.: Form for displaying records

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